Passive and renewable low carbon strategies for residential buildings in hot humid climates

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PASSIVE AND RENEWABLE LOW CARBON STRATEGIES FOR RESIDENTIAL BUILDINGS IN HOT HUMID CLIMATES

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Abstract

The building sector alone accounts for almost 40% of the total energy demand, whereas people spend more than 80% of their time indoors. Reducing the energy demand in buildings is crucial to the achievement of a sustainable building environment. At the same time, it is important not to deteriorate people's health, well-being and comfort in buildings. Thus, designing healthy and energy efficient buildings is one of the most challenging tasks. The housing industry in Oman overlooked the energy consumption of buildings and their adverse impact on the climate. This led to an increased energy consumption and its associated CO_2 emissions. Hence, this research aims to experimentally evaluate the key elements and strategies required to increase the adoption of lifetime low-carbon domestic buildings in Oman, that will provide the most benefits towards a more sustainable energy future.

In order to achieve the aims stated above, a comprehensive, multi-stage study has been conducted, involving the review of the status of low carbon buildings in the GCC countries and in Oman compared to the global scale. The technical viability of low-energy codes and standards for domestic buildings in the Sultanate of Oman were then examined in order to identify the factors resulting in increased energy consumption. These factors include a regulatory framework, market support, as well as the wellness and awareness of the society with respect to sustainability. Thereafter, the research identified the main elements of the operational deficiency interfering with the adoption of low carbon buildings. This covered the status of the housing stock typology in Oman, building energy consumption characteristics and usage patterns, occupant behaviours, regulation and government support. Accordingly, a roadmap was suggested for low carbon strategy to help the country overcome the adverse effects of energy usage in domestic buildings.

In this context, each stage of this research utilised a specific methodology including public survey analyses, site visits, modelling analyses and expert consultation using an analytical approach. Furthermore, the research methodology incorporated a comparative analysis for the samples of the buildings including conventional and low carbon buildings in the Sultanate of Oman using descriptive, qualitative and spatial analyses for these case studies.

In addition, the study reviewed the key features characterising the energy efficiency of low carbon buildings in the hot humid climate through the assessment of a set of energy efficiency measures (EEMs) for residential buildings in the selected climate. These EEMs involved the building envelope, building shape, orientation, materials, glazing, insulation, shading, natural ventilation, daylight and the application of renewables. Subsequently, a low carbon domestic building design template was established that supports architects, civil engineers and building professionals in the design of sustainable homes for the selected climate, context and cultural requirements. The template was designed to evaluate the overall building energy consumption based on building physics and the operation pattern and provided the energy evaluation for the proposed design in order to maximise energy savings. Then, the template was tested on the energy use of viable housing prototypes employing the criteria of the established template.

This study contributes to the body of knowledge within this field by offering a low carbon domestic framework for the design of low energy residential buildings in Oman. It proves that it is possible to reduce the energy consumption of residential buildings due to the application of each EEM by 3.7% to 18.2%. Furthermore, the research identified the possible lower and zero cost EEMs which can be implemented in the context of Oman. The findings are broadly applicable to other regions with similar climatic conditions and cultural constraints, such as those of the Middle East and the GCC countries. The results showed that different sets of actions are required to achieve the building energy performance in the researched country's case study.

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I would like to thank everyone for their support and encouragements, which have made this thesis possible. This research would not have been possible without the support and advice given to me by my two supervisors. I would like to express my sincere gratitude to my first supervisor Dr Steve Lo for this invaluable help throughout the entire PhD research and his confidence in my ability to carry out the investigation. His guidance helped me throughout the research and writing of this thesis. I would also like to thank my second supervisor Dr Sukumar Natarajan for his support and guidance throughout the entire study.

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Finally, I am deeply grateful for my family, relatives and my mother who has always been my great teacher, and for my friends and colleagues for their help and unlimited support.

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List of Abbreviations

ANRE	*Agence Nationale de Régulation de l'Energie*
AC	Air-Conditioning
ACCA	Air Conditioning Contractors of America
BEI	building energy index
ARZ	Building Rating System
BREEAM	Building Research Establishment Environmental Assessment Method
BEE	Bureau of Energy Efficiency
CO_2	Carbon Dioxide
CIBSE	Chartered Institute of Building Services Engineers
COAs	Continuously occupied areas
CBs	Conventional building
CDDs	cooling degree days
DECs	Display Energy Certificates
DHW	Domestic Hot Water
ECO	Energy Conservation and Commercialization
EEI	Energy Efficiency Index
EEMs	Energy Efficiency Measures
EnEV	Energy Saving Regulation
GSAS	Global Sustainability Assessment System
GHG	Greenhouse gases
GCC	Gulf Cooperation Council
TC06	Gulf Technical Committee
HDDs	Heating degree days
IESVE	IES Virtual Environment
IPCC	Intergovernmental Panel on Climate Change
ICC	International Code Centre
IEA	International Energy Agency
IECC	International Energy Conservation Code
IgCC	International Green Construction Code
IIEC	International Institute for Energy Conservation
LEED	Leadership in Energy and Environmental Design
LGBC	Lebanon Green Building Council
LPG	Liquefied petroleum gas
LCB	Low Carbon Building
MENA	Middle East and North Africa
NASA	National Aeronautics and Space Administration
NCBB	National Committee of Buildings in Bahrain
NCC	National Construction Code
NOAA	National Oceanic and Atmospheric Administration
OPWP	Oman Power and Water Procurement Company
PV	Photovoltaic

QCS 2010	Qatar Construction Specifications
REMM	Reactive Energy Management Model
ASHRAE	Refrigerating and Air-Conditioning Engineers
RE	Renewable energy
R-BEET	Residential Building Energy Efficiency Template
SBC	Saudi Building Code
SBCNC	Saudi Building Code National Committee
SSE	Scottish and Southern Energy
SHGC	solar heat gain coefficient
SOTA	state-of-the-arts
SA	surrounding area
TA	task area
ECQ	The Energy City Qatar
GSO	The GCC Standardization Organization
GORD	The Gulf Organization for Research and Development
TRC	The Research Council, Oman
TES	Thermal Energy Storage
UNFCCC	United Nations Framework Convention on Climate Change
USAID	United States Agency for International Development
USGBC	US Green Building Council
WBDG	Whole Building Design Guide
WWR	window-to-wall ratio

1 Chapter 1: Introduction

1.1 Background

Oman is one of the six Arab States in the Arabian Peninsula that form the Gulf Cooperation Council (GCC). These countries are well known of their production and large reservoirs of crude oil and gas. The reserves of oil in these countries are 30.5% of the total global proven reserves (Al-Maamary, Kazem and Chaichan, 2016), as well as an estimated 21% of the total world proven gas reserves (Ferroukhi et al., 2016). As a result of rising oil prices in the 1970s, GCC countries used the significant revenues generated from the oil industry to build new modern cities and their associated infrastructure. Thus, the oil wealth has been reflected in considerable changes in life style patterns and standards of living. In the past 40 years, many new cities and residential developments were created to accommodate the rapidly increasing population. Similarly, the construction industry changed to meet the modern demands of local communities. New construction materials such as concrete, steel, asbestos and plasterboards were introduced, and building design and features changed to suit these developing life styles. The growing rate of urbanisation, and changes in life patterns have resulted in an increase in energy consumption per capita. During the period from 2012 to 2020 the energy consumption of GCC countries is expected to continue increasing by 5.4% to 6.0% per annum (The GCC in 2020: Resources for the future, 2017), whereas the recorded global average is 2.2% (Alnaser et al. 2008). Similarly, in 2012, the annual electricity report presented by Oman Power and Water Procurements Company stated that the average annual increases in electricity consumption were 7.1% and 8.4% for the two main electricity utilities, and the company expects the growth of electricity demand to be between 8% and 10% annually for the period 2012 to 2018 (SAOC, 2012). In 2012, the electricity energy consumed by the residential sector in Oman was 48% of the total consumption, whereas an energy report presented by Earth Trends Organisation in 1999 shows that the residential energy consumption was only 9%. Hence, demand for electricity will keep rising in the absence of a domestic building energy strategy.

As oil and gas are considered to be explicitly related to a nation's wealth, all GCC governments provide subsidies to support energy prices for the public, making the energy sector solely dependent on these fuel sources, despite the potential availability of promising renewable energy alternatives (Al-Badi *et al.,* 2011). Low energy prices encourage a profligate use of energy, and demonstrate an unsustainable way of utilising natural resources where the consumption of energy per capita in Oman exceeds world average consumption rates. Unwise consumption of these natural sources was regarded as a loss to the national economy. According to HSBC estimations, at the current rate of energy consumption, Saudi Arabia would require about $170 billion of fossil fuel for the next 10 years (Brookings, 2013). Energy consumption in domestic buildings in GCC countries is recorded as being among the highest in the world (Taleb and Pitts, 2009). However, it is possible to achieve a major saving in local energy consumption by introducing low carbon building technologies and adopting a more appropriate deployment of renewable energy technologies (Bhutto *et al.,* 2014).

Since the consumption of fossil fuel is one of the major driving factors of climate change, it has raised awareness of the need to reduce local energy consumption. The Intergovernmental Panel on Climate Change (IPCC) stated that the energy consumption in developing countries is responsible for 40 % of greenhouse gas generation (IPCC, 2007). In fact, these values may increase, since energy use and related emissions may double or potentially even triple by mid-century due to several key facts, including a more rapid consumption of energy associated with the accelerated economic development of developing countries (Lucon *et al,* 2014). Hence, emissions of CO_2 from energy usage will remain at their current high levels or may even increase as the use of fossil fuel continues to rise. The residential sector is considered to be one of the major areas of energy consumption worldwide, accounting for 40% of total energy consumed (Chen *et al.,* 2011; Paudel *et al.*, 2017).

In the past few decades, the development of low carbon and zero energy buildings has become a major area of interest for many countries (Isiadinso *et al.,* 2011). Intensive studies conducted around the world showed the need to adopt renewable energy, to increase its share of total energy consumption and to ensure security of energy supplies (Doukas, *et al.,* 2006; Chastas, Theodosiou and Bikas, 2016). Many developed countries have formulated regulations and guidelines with energy performance residential building targets. For example, in 2006 England and Wales clearly stated that new buildings in 2016 should be net zero carbon buildings (Pan and Garmston, 2012). Finland decided to implement the Passive-house standards to all new constructed buildings from 2015 (Brēmere, Indriksone and Aleksejeva, 2013). France aims to achieve energy positive buildings for all new buildings from 2020 onwards, and Germany intends to prevent the usage of fossil fuel in all new buildings by 2020 (Koch, Girard *et al.,* 2012).

Until recently, Gulf countries have not developed any policies to reduce CO_2 emissions or encouraged the use of renewable energy technologies. The six countries listed in the GCC are in the top 10 countries of CO_2 emission per capita (Reiche, 2010). Greenhouse gases (GHG) emissions per capita in the GCC are at least two to three times higher than the average in the EU-15, while compared to GDP, the GHG emissions are almost four times higher (Papadopoulou *et al.*, 2013). In addition, their residents generate two to ten times the amount of CO_2 emissions of the average global citizen (Hussain, 2014). However, in 2005 Oman and other GCC countries signed and ratified the United Nations Framework Convention on Climate Change (UNFCCC), and accessed the Kyoto Protocol (Doukas *et al.* 2006). Since then the energy and CO_2 policy of these countries has changed, and renewable energy has now become an option for investigation in many Gulf countries. This is evident in the scale of investment in this option and decisions taken in the direction of sustainability. The Energy City Qatar (ECQ), established in Qatar and Masdar City in the UAE, shows the current commitment of these countries to move to a more sustainable energy environment. Apart from their accession to the Kyoto Protocol and, their involvement in and ratification of UNFCCC, their commitment to renewable energy was driven by the rapid increase in energy consumption demanded by the development in these countries. There have been a number of studies carried out in these countries showing the potential of using renewable energy as replacements for current conventional energy supplies (Doukas *et al.*, 2006). Oman's vision 2020 is aiming to achieve 10% renewable energy by the end of the 8^{th} five-year plan (Oman Solar, 2017).

1.2 Building and climate change

The average earth temperatures are rising due to increases in the present levels of greenhouse gases in the atmosphere. Scientists have linked the increase in the levels of atmospheric GHGs to industrial activities and increases of urbanisation (IPCC 2014). The Copenhagen Climate Summit in 2009 targeted to limit this increase to 2.0 ºC by 2020. However, with current progress, it is not possible to achieve this target and the average temperature will keep rising if the governments do not implement policies to control GHG emissions. The annual earth surface temperature records from 1880 to 2014, that are monitored by the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), the Japan Meteorological Agency, and the Met Office Hadley Centre (United

Kingdom), show increasing trends. Furthermore, all four records show that the last decade was the warmest (Figure 1.1) (Carlowicz, 2016). Such changes in global temperature will result in severe environmental consequences that include flooding, droughts and disturbance to ecological systems.

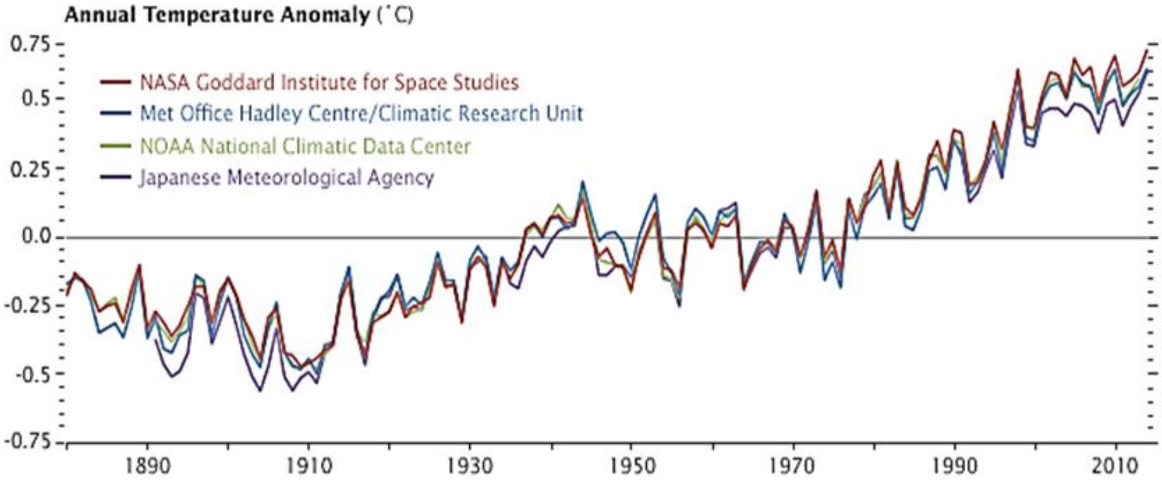


Figure 1.1: Yearly earth surface temperature records (Carlowicz, 2016)

1.3 Oman geography and climate

Oman is located in the Middle East in the south-east corner of the Arabian Peninsula. It has an area of 309,500 km^2, and is situated between latitudes of 16^{O} 40′ N to 26^{O} 20′ N and longitudes of 51^{O} 50′ to 59^{O} 40′ E. It has 1700 km of coastline extending from Hormuz in the north to the boarder of the Republic of Yemen on the southern part of the sultanate, overlooking three main seas: the Arabian Gulf (Persian Gulf), the Sea of Oman (previously known as the Gulf of Oman) and the Arabian Sea. Omani topography varies between deserts, (about 82%), and Mountains, (15%), with the remaining being valleys and oasis (Kazem, 2011). The administration structure of the country consists of 9 governorates. According to data from the National Centre for Statistics and Information the total population of the country in March 2017 was 4.5 million, mostly concentrated along the coast and mainly in three governorates in the northern part of the country (Monthly Statistical Bulletin, 2017). Thus, this study will focus on these three governorates where the greatest population densities are located. As per the general census conducted in 2010, the total available housing units were 540,770, consisting of individual houses (villa), flats, and apartments. Furthermore, the residential sector is expanding rapidly, the number of new residential plots distributed to the citizen increased in 2015 by 45% from its value between 2010 and 2014.

The climatic condition of Oman is hot and humid in the coastal regions, and hot and dry in the interior of the country (Figure 1.2). The weather data for 2012 shows that the highest recorded temperature in the country was 50ºC in Khasab, the minimum temperature was -1ºC in Saiq, the highest recorded humidity was 100% in Sohar and the lowest humidity was 1% in Jabal-Shams. However, Oman's climate is defined by the Köppen-Geiger climate classification as a hot arid desert climate (Figure 1.3).

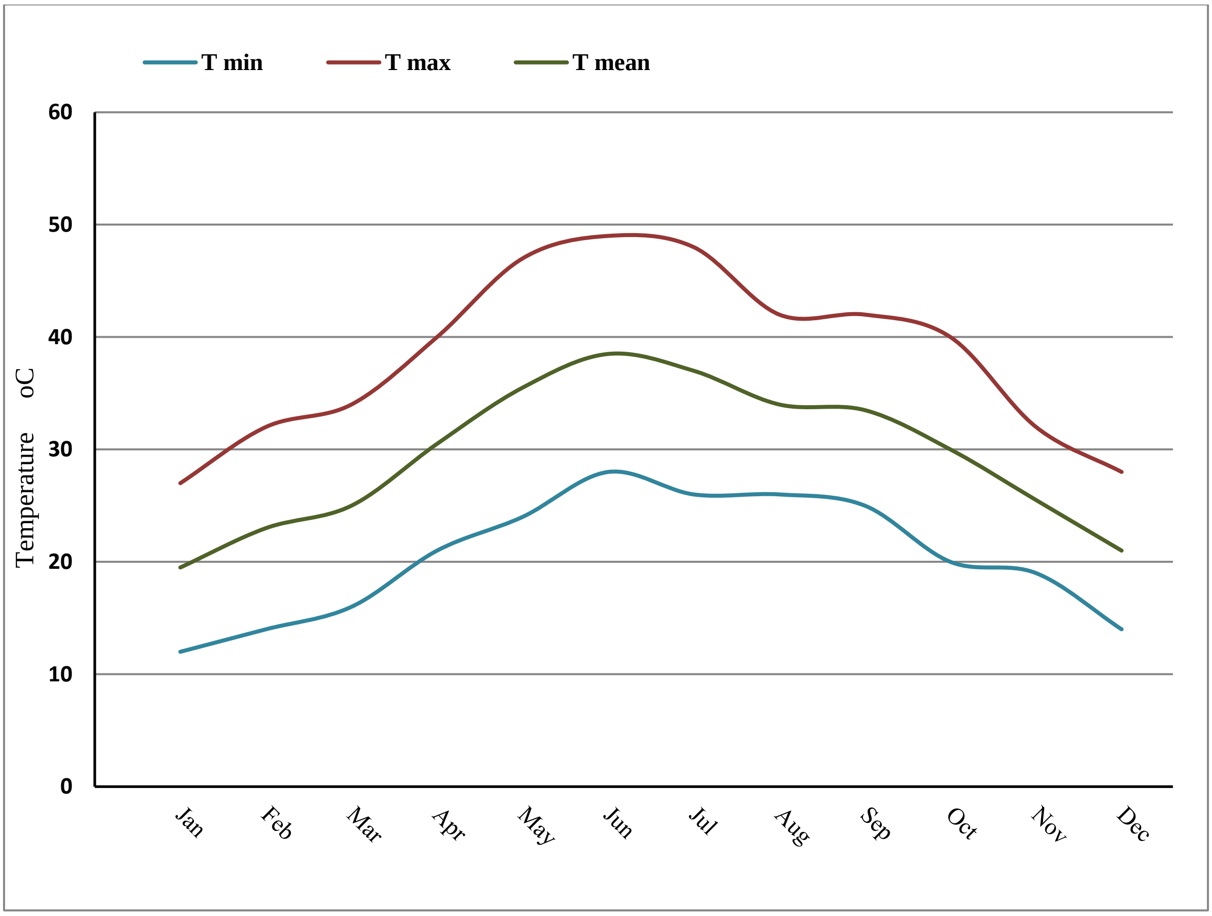


Figure 1.2: Muscat monthly maximum and minimum temperature 2016

(Source: reproduced from data presented by National Centre for Statistics and Information)

However, whilst the Koppen Classification system can be used to classify climate and environmental conditions for any location in the world, it is difficult for designers to use when relating local climate to energy-reduction design strategies (Aksamija, 2013).

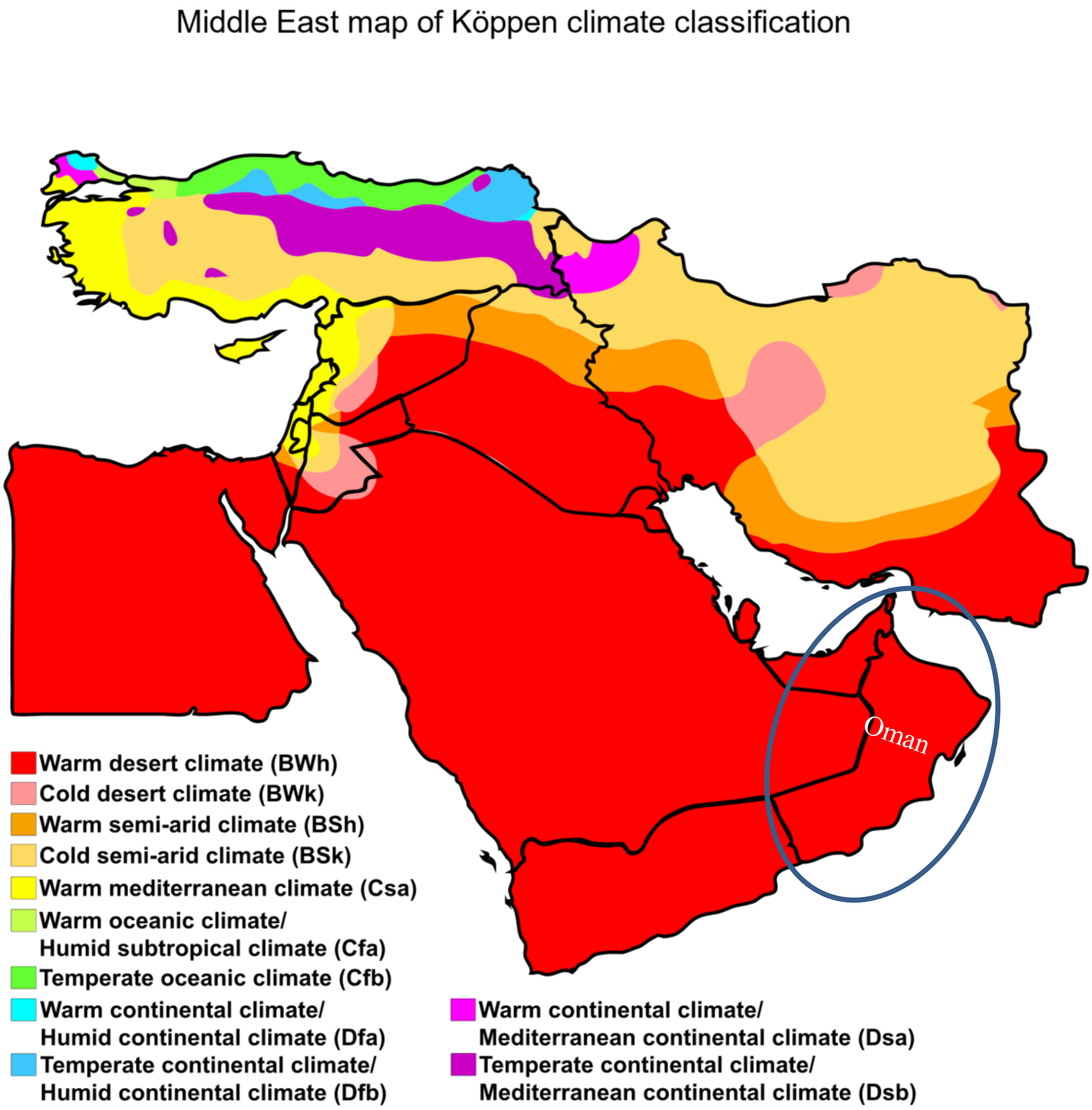


Figure 1.3: Oman climatic conditions map

(Source: World Map of the Köppen-Geiger climate classification)

1.4 Construction practice in Oman and GCC countries

In Oman and other GCC countries, construction practices are dictated mainly by social, economic and climate drivers. These factors include available materials, social and traditional norms, cost and finally, weather conditions. Therefore, changes in construction practice occur according to changes in any one of these factors. Before the 1970's, houses design and construction practice followed passive design strategies because the construction industry relied on local materials and the environmental features of the site (Al-Hinai, 1993). The main reasons were due to severe shortages of energy resources, limited local construction materials and less financial capability to import materials from overseas. Climate conditions played a major role in building design and in the selection of construction materials worldwide. In the past, the vernacular architecture of Oman has managed to provide acceptable thermal comfort by an evolving methodology and systems that were in harmony with the climate conditions and local environment. Thus, buildings in the coastal regions were built facing towards the sea to benefit from onshore sea breezes. In other regions of the country where humidity was relatively low, mud was used as a common construction material to provide a sufficient thermal barrier to reduce heat gain in summer (Al-Hinai, 1993) (Al-Badi *et al*., 2011).

During the last four decades, Omani construction practice has aligned to more contemporary construction practices. Nowadays, concrete is one of the most widely used materials, whereas local traditional materials have gradually disappeared from the construction industry. This has happened because concrete gives more design freedom, enabling larger, more durable and longer life span buildings. Equally, affordable mechanical air conditioning units became available, giving the building designer more freedom to avoid the restrictions of the natural thermal comfort requirements in the design. Therefore, concrete block buildings were constructed without considering their energy performance during operation, as the design and orientation of buildings did not exploit the beneficial features of local environments. This led to highly energy inefficient buildings, which is apparent from the amount of annual energy consumption of buildings and the huge variation in energy bills between winter and summer. Hence, a need exists to extend low carbon building strategies to the Sultanate of Oman, wherein there is a surge in the energy consumption per capita. It has been found that the summer energy demands of cooling devices in buildings and other home appliances reached new peaks leading to a depletion of local energy sources, which also affect occupant's quality of life and negatively influenced the environment of Oman. For some residential buildings summer energy consumption rose to seven times its value in winter. This seasonal variation of energy needs added stress on electricity utilities to produce energy when it was needed most (Al-Badi *et al*. 2011).

According to the Oman Chamber of Commerce and Industry (2017), there are 720 companies registered in grade one as excellent in the construction sector. These companies are concrete based construction practices. However, in 2008 the first Rapidwall building was constructed by one of these companies as a promising new construction method that could reduce building energy consumption (Rapidwall, 2009). It is made of gypsum fibre reinforced walls as an innovative solution widely accepted and implemented in Australia and India. Rapidwall consisted of fibre reinforced gypsum panels made in a factory and transported for erection on site. This construction method was first used in Australia in the 1990s, and was then used in China and India (Said Meselhy & ElSaeed, 2016). However, in Oman its use is still limited to government projects when time and construction duration is important. Thus, based what has been mentioned previously in this chapter the following statements can be made:

- In the past four decades, urbanisation in Oman and other GCC countries has increased rapidly (Figure 1.4) and this is set to continue for the next few decades due to the increases in economic development.
- The energy sector is dominated by fossil fuel use, which is depleting natural resources, and renewable energy sources are hardly deployed.
- The current residential sector is considered as inefficient in its energy use, consuming 48% of the total country energy consumption in 2012 (SAOC, 2012). This percentage is greater than it was in 1990 and higher than the world average.
- Despite the targets set for renewable energy use by 2020, there is still no government policy to involve the residential sector in achieving this goal.
- The construction regulations in Oman do not include local codes of sustainability. Until recently, the construction of low carbon buildings was neglected, and has never been an option for new buildings, which included buildings constructed for the government sector.

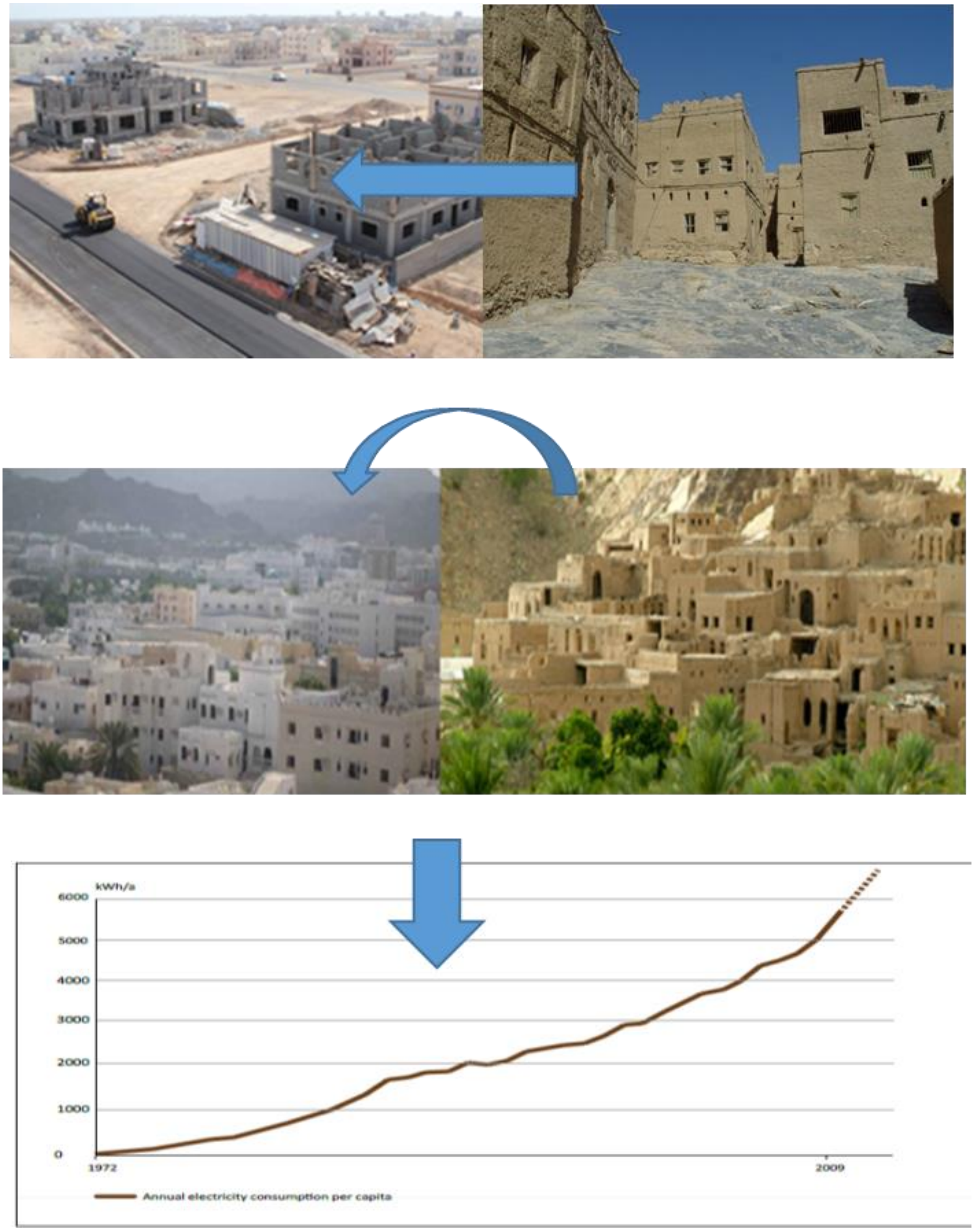


Figure 1.4: Historical changes of Oman's building construction and energy use

1.5 Importance of the research

Building energy consumption and carbon emissions associated with domestic buildings has been researched extensively in many countries around the world (Chen S, *et al*., 2014) and the topic of low carbon building has been under increasing investigation in recent years (Napolitano *et al*., 2012). In the developed countries, a great deal of effort has been spent to encourage and enhance the energy performance of buildings in order to reduce overall energy demand. However, in the Gulf countries, particularly in Oman, less consideration has been given to this important issue. It is estimated that 48% of the electricity usage in Oman is consumed by residential buildings (Figure 1.5) (Monthly Statistical Bulletin, 2017). Therefore, if these issues are not resolved now, the energy sector will soon not be able to satisfy the increasing energy demands and the 10% renewable energy target by 2020 will not be achieved. CO_2 emission per capita might be increased and existing conventional energy sources would be consumed faster. Hence, a need exists to develop a strategy for a sustainable construction sector to overcome these problems. To overcome this problem there is a need to promote building energy efficiency and develop energy performance criteria and a viable implementation strategy.

This research will endeavour to resolve these problems by devising a low carbon building strategy. This strategy will be based on exemplars of low carbon buildings in the country to provide a set of criteria and validated recommendations that will enable better home energy operation and reduce the carbon footprint of residential buildings. This study will attempt to direct the current construction industry in Oman towards a more sustainable future by developing low-carbon guidelines and template for an energy calculation tool for residential buildings with less embedded cost.

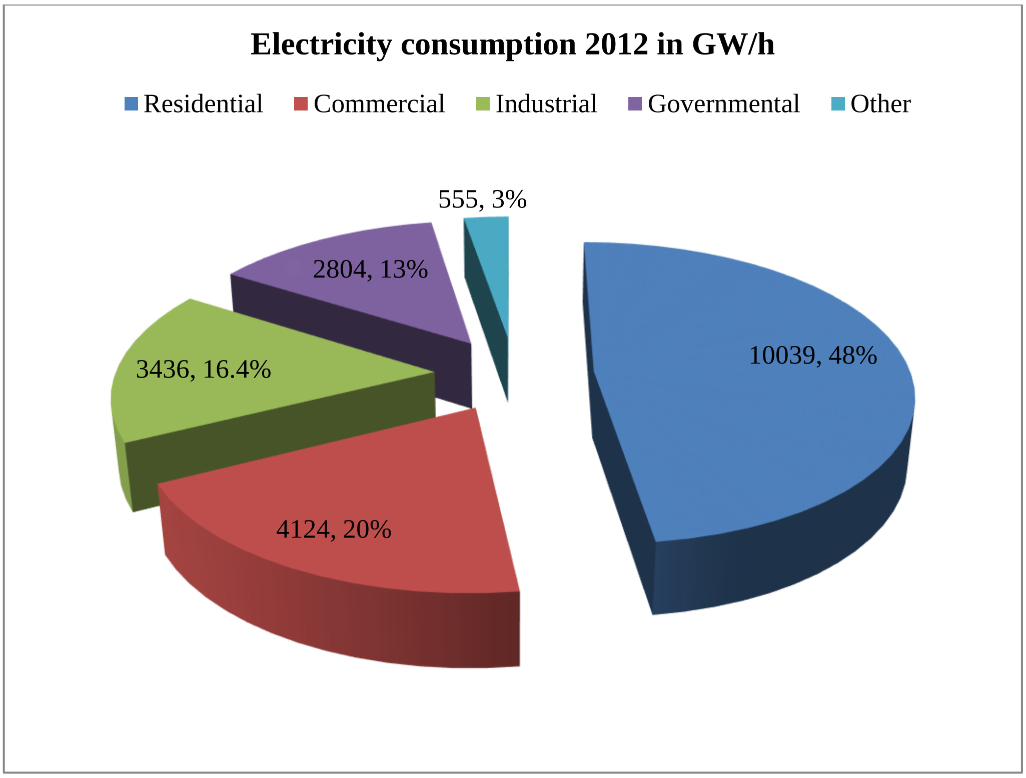


Figure 1.5: Oman 2012 Electricity consumption per sectors

(Source: reproduced from data presented by National Centre for Statistics and Information, 2016)

1.6 Hypothesis

The hypothesis set for the study is:

The absence of a low carbon residential building strategy in Oman has led to unsustainable consumption of energy and air-conditioning energy usage. This can be reduced by applying suitable low-carbon design criteria optimised for hot humid climates.

1.7 Aim of the research

Although the key elements characterising low carbon building have been defined, they have not been experimentally validated for countries like Oman. Therefore, the aim of this research is to establish a passive and renewable low carbon strategy for residential buildings in hot humid climates through experimentally evaluating the energy efficiency of key elements.

1.8 Objectives

To meet the aim of this research, a systematic approach for evaluating building energy performance in Oman was established based on the following objectives and goals:

Objectives	Chapter	Chapter goal
All objectives	1. Introduction	Provides background to the research topic, identifies of the aim and objectives of the research and its importance and contribution to the existing body of knowledge.
I. Review the regulatory and energy context of state of the art (SOTA) practice of low-carbon domestic building and construction in Oman.	2. Current low carbon practice, barriers and deficiencies	Presents a review of the up-to-date status of low carbon building, relevant standards and regulatory framework at international level, Middle-East and North Africa MENA, GCC countries level and Oman to identify factors leading to key knowledge gaps.
II. Establish research methodology suitable for the research topic	3. Research methodology	Examines internationally recognised research, and methodologies adopted in this field and describes how data is collected, analysed and examined to support the main hypothesis.
III. Determine key elements of operational deficiency that increases energy consumption of residential buildings in Oman	4. Main elements of operational deficiency	To determine the level of awareness surrounding energy efficiency in residential buildings.
IV. Determine building energy system boundaries, needs and requirements.	5. Domestic building energy systems in Oman	Established the building energy system to identify the key attributes for the low carbon building for a hot and humid climate.
V. Develop design guideline framework for LCB based on Energy Efficiency Measures (EEMs) for hot climate including: • Design criteria • Building elements • Building materials	6. LCB design guideline framework	Propose low carbon design guideline framework based on the optimal application of Energy Efficiency Measures (EEMs) used in SOTA LCBs in hot humid climate using a case study approach of whole building energy-systems
VI Devise a LCB template to evaluate options of residential LCB in Oman considering; • Energy requirements • Building operation • Home appliances	7. Low carbon building energy template	Present a LCB energy template for an energy calculation tool capable of evaluating different options for the energy efficient design of residential buildings in Oman based on performance targets, usage profiles and building characteristics and typologies.
VII. Map a suitable LCB strategy for Oman using the outputs of the LCB template.	8. Roadmap for Oman's LCB strategy	Propose a Roadmap of the benefits of the most appropriate LCBs and EEMs to adopt for Oman's current energy status.
All objectives	9. Discussion	Discuss the implications and potential impact of the research findings, their limitations and future application.
All objectives	10. Conclusion	Shows the extent to which each objective has been fulfilled and identifies areas for future research.

Table 1.1: Thesis objectives and structure

1.9 Scope and limitation of the research

The scope of this study is limited to the validation of low carbon building strategies for single family dwellings in the hot humid climate of the sultanate of Oman (Figure 1.6). Single family residential buildings were selected as the subject of this research because it is the most common resident typology in Oman (Monthly Statistical Bulletin, 2016). Research will involve a review of Omani legislation and current construction practices and compare them with those from other GCC countries that have implemented Low Carbon Building strategies. Furthermore, the regulations and data from other GCC countries will be considered in this research.

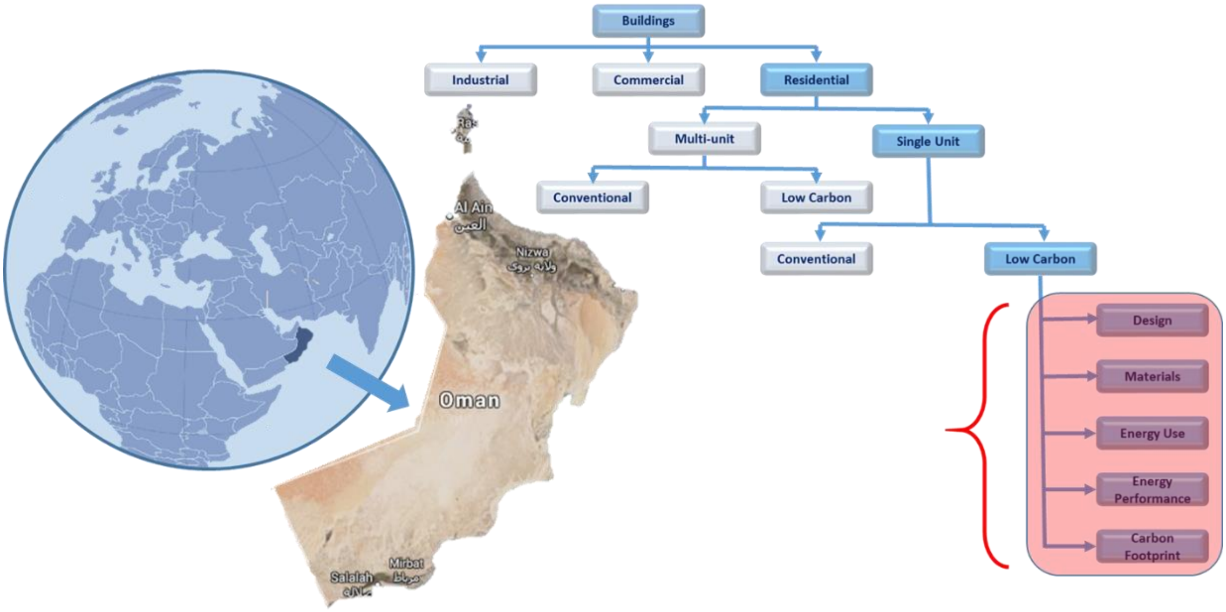


Figure 1.6: Limitation of the research

1.10 Contribution to the body of knowledge

The challenges for the construction sector and its clients in Oman are not only to examine targets for low carbon buildings in Oman, but also to identify how the country can meet these targets within the context of local social, economic and environmental constraints. The key problem related to this issue is the absence of a ‘building energy performance’ policy. Hence, this study is focused on devising a low carbon strategy for building energy performance in its hot humid climate. In this regard, the research seeks to answer the following research questions:

- What is the status of low carbon building in GCC countries compared to international benchmarks?
- What is the level of awareness of stakeholders on energy conservation in residential buildings?
- What are the main barriers to the wide spread development of low energy houses in Oman?
- What is the current energy consumption of residential buildings compared to available state of the art low energy buildings in Oman?
- What are the main attributes characterising low carbon buildings in hot humid climates?
- How can Oman improve energy efficient building design and resolve the problem of the low adoption of energy effect dwellings and what is the potential support required?

Hence, by answering these questions, the original contribution to the body of knowledge within the context of this research are:

- **Established monitoring methodology:** Through Simulation and field experiments
- **Design criteria:** design criteria for low carbon building technologies and strategies in hot humid climates.
- **Benchmarking:** benchmark the energy consumption of residential buildings in for the selected case study exemplars.
- **New predicting tool:** Innovative building energy template developed to develop an energy calculation tool that evaluates residential building energy Residential Building Energy Efficiency Tool (R-BEET)
- **Market value:** Cost benefits evaluation of low carbon building options in the selected research case study country.

2 Chapter II: Current low carbon building practice, barriers and deficiencies

2.1 Introduction

The energy consumption of buildings accounts for nearly 40% of the recorded global consumption of primary energy resources and is responsible for 24% of the world's CO_2 emissions (Shen *et al.*, 2016). Hence, the energy performance of buildings received increasing concern from researchers, the government, and non-governmental organisations in the past decades in an attempt to improve energy conservation. Many researchers believe that the energy performance of buildings can contribute to preventing global climate change, if we endeavour to build and rebuild more energy efficient buildings (Olonscheck, Holsten & Kropp, 2011; Brown *et al.*, 2015). Furthermore, the use of technology at the operational stage, along with the awareness of the communities with respect to energy consumption alongside with the implementation of practical regulations and standards will substantially reduce the overall energy consumption of the buildings sector (Curtis & Pentecost, 2015); (Shen *et al.*, 2016). The oil crises in the 1970s (Ward *et al.*, 2011) alongside rapid development of developing countries have raised global concerns in relation to the energy conservation in the industrial, transport and building sectors (Iwaro & Mwasha, 2010). Accordingly, developed countries have devised regulations and standards to improve the energy consumption of their buildings (Iwaro & Mwasha, 2010). Today energy efficient buildings, low energy buildings and zero energy buildings are common practice in most developed countries (Papineau, 2017). Conversely, some of the Gulf Cooperation Countries (GCC), such as Oman, have not taken any steps to conserve energy in the building sector, such as periodically updating legislation and standards. The absence of governmental concern and awareness of the public in relation to energy conservation resulted in an increased energy consumption of the residential building sector (Reiche, 2010).

In this context, the aim of this chapter is to review the status of low carbon buildings (LCBs) in Oman compared to GCC countries, the MENA region and at an international level. Furthermore, the review focuses on the regulations and standards, construction practice, materials, vernacular architecture and energy consumption of residential buildings in Oman in order to identify the gaps in knowledge that has led to a reduced adoption of low carbon building in the gulf countries with a main focus on the status of Oman.

2.2 The concept of energy and building

Energy conservation has become an important part of national energy strategies for many countries and will continue growing in the future (Kaynakli, 2008). Managing the energy use in buildings is a critical task for the main partners of the building industry, as it is controlled by several factors. Energy consumption in buildings is affected by the local culture of the occupants, climate conditions, and energy strategy and policies of the country (Xu *et al.*, 2013). Hence, the energy consumption of buildings varies across countries on the basis of their social, environmental and economic status. This is one of the main reasons for the variety of regulations and standards across the world. Therefore, it is difficult to precisely define the magnitude of energy consumption required for low carbon buildings suitable for all countries (Andaloro *et al.*, 2010). For example, the annual energy consumption for home heating across the 27 members of the European Union (EU) is 2,299 TWh with an average consumption of 152 kWh/m^2. The annual consumption varies across the members states, from 19kWh/m^2 in Malta to 215 kWh/m^2 in Latvia (EU, 2009). Therefore, what is considered to be low energy practice in one country may not be considered as good practice in another country. This means that an efficient energy practice in one country that helps to reduce the energy consumption in buildings in a particular location may not be suitable for another location characterised by a different cultural backgrounds, climate conditions, availability of building materials or economic conditions. In this regard, many developed countries have set up a plan for energy conservation in the building sector in order to fulfil their local conditions. From this prospective, these countries established official standards to define the band of energy consumption in residential buildings using kWh/m^2 per year metrics based on the country's energy policy, taking into consideration the climate, culture and occupants` needs. Currently, energy conservation in buildings remains an objective to be addressed by many countries in order to achieve a sustainable environmental and secure economic development. An example of legislation on energy in buildings is the Energy Star label in the US, which is awarded to houses that use 15% less energy than specified by the regulations imposed on typical new homes (EU, 2009).

The European Union and other developed countries have reached an advanced level in the status of low energy buildings, whereas most of the GCC countries have still not developed a clear policy for energy conservation in the building sector (Papadopoulou *et al.*, 2013; Alhorr & Elsarrag, 2015). A review on the status of low carbon buildings and low carbon building strategies in the GCC countries compared to the international status shows that these countries are still lagging behind and the need still exists to either establish a clear vision or update the existing strategies and regulations in order to promote the implementation of low carbon buildings.

2.3 Review of related international standards on energy conservation in buildings

International energy codes and standards are set to offer minimum/maximum acceptable values of energy consumption of buildings in order to help designers meet the required efficiency for a design that can achieve an optimal energy use and carbon emission (Fossati *et al.*, 2016). Therefore, an energy efficient building is required to comply with the available energy codes/standards or, may perform better than what has been set in the codes, to be classified as an efficient building. These regulations are normally classified according to the building type and climate zone with mandatory and compulsory options (Fossati *et al.*, 2016). The objective of the energy conservation code is to improve the overall sustainability of buildings by setting a single standard for the construction industry to design and build housing exerting a low impact on the environment. The 2006 edition of the International Building Code (USA) stated: *"the purpose of code is to establish the minimum requirements to safeguard the public health, safety and general welfare through structural strength, means of egress facilities, stability, sanitation, adequate light and ventilation,* ***energy consumption****, and safety to life and property from fire and other hazards attributed to the built environment and to provide safety to fire fighters and emergency responders during emergency operations*." According to the International Energy Agency (IEA), the 2008 building energy codes were also referred to as "energy standards for buildings", "thermal building regulations", "energy conservation building codes" or "energy efficiency building codes". They were the key policy tools used by governments to reduce the energy consumption of buildings. Codes normally consist of a set of mandatory minimum energy performance requirements in the design to regulate the energy use in buildings. They may cover both new buildings and existing buildings undergoing renovation or alteration. In this regard, architects and engineers follow the instructions stated in the codes to design buildings that meet the required energy performance. The most well-known codes and standards that are concerned with energy conservation in buildings on a global scale are:

1. **The International Energy Conservation Code (IECC):** A building code established by the International Code Council in 2000. This is a model code used in many states in the United States to set the minimum requirements for the design and construction of energy efficient buildings (International Energy Conservation Code, 2012).

2. **ASHRAE 90.1 (Energy Standard for Buildings Except for Low-Rise Residential Buildings)**: The US standard provided for the minimum requirements of low energy buildings except for low-rise residential buildings. The first version of the standard, ASHRAE 90 was published in 1975. Then in 1999, the Board of Directors for ASHRAE voted to place the standard on a continuous upgrade based on the rapid changes in energy technology and energy prices (ASHRAE standard, 2010). The standard was renamed as ASHRAE 90.1 in 2001. Since then, several editions and updates have been made to the original version in 2004, 2007, 2010, and 2013 considering newer and more efficient technologies (ASHRAE 90.1, n.d.). Standard 90.1 has served as a benchmark for commercial building energy codes in the United States and as a key basis for codes and standards around the world for more than 35 years (Standard 90.1 | ashrae.org, n.d.).

3. **ENERGY STAR:** It is a trademark in the United States standards used for energy efficient products. It was established in 1992 by the US Environmental Protection Agency and Department of Energy (History & Accomplishments, n.d.). Since then, it has been successful in achieving substantial market penetration and influencing consumer decision-making (Tonn *et al.*, 2013). Products having the Energy Star mark label including kitchen appliances, buildings and other products may use up to 30% less energy than what standard appliances require (Ward *et al.*, 2011). In the US, the label is displayed on appliances certifying them as qualified products (Energy Savings at Home, n.d.).

4. **ASHRAE Standard 189.1:** It is the standard for the Design of High Performance, Green Buildings Except Low-Rise Residential Buildings. It provides a comprehensive building

sustainability guidance for the designing and operation of high-performance green buildings. The standard sets the foundation for green buildings based on the review of site sustainability by addressing the water use efficiency, energy efficiency, indoor environmental quality (IEQ), the building's impact on the atmosphere, materials and resources (Understanding Standard 189.1 for High-Performance Green Buildings | ashrae.org, 2014).

5. **2012 International Green Construction Code (IgCC):** This code has been developed in the USA by the International Code Centre ICC in collaboration with the American Institute of Architects (AIA), ASTM International, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Illuminating Engineering Society (IES) and US Green Building Council (USGBC) in order to establish the minimum regulations for building systems and site considerations using performance-related provisions. The release of the public version 1.0 was announced by ICC on March 11, 2010, and the current available version is the 2015 IgCC, whilst the upcoming version will be released in 2018 (IgCC | ICC, 2017).

6. **Building Code of Australia BCA 2006**, National Construction Code (NCC) introduced the energy efficiency requirements for implementation in 2003 with detached housing and now applies to all the classifications of buildings covered by the NCC. The current version of the code is the NCC 2016 Volumes One, Two and Three, which are a uniform set of technical provisions for the design and construction of buildings and other structures throughout Australia and provides the thermal performance of the house and its domestic services. The next version of the code is planned for publication in 2019. (NCC Volume Two Energy Efficiency Provisions | Australian Building Codes Board, 2015).

7. **The Indian Energy Conservation Building Code (BEE 2006)** has been developed by the International Institute for Energy Conservation (IIEC) under contract with the United States Agency for International Development (USAID) as part of the Energy Conservation and Commercialization (ECO) Project providing support to the Bureau of Energy Efficiency (BEE) Action Plan. The purpose of this code is to provide minimum requirements for the energy-efficient design and construction of buildings. The code is mandatory for commercial buildings or building complexes that have a connected load of more than 500 kW. The code is also applicable to all buildings with a conditioned floor

area greater than 1,000 m^2. Furthermore, the code can be recommended for all other buildings (Energy Conservation Building Code User Guide, 2009).

8. **Building Regulations (Part L) for UK and Ireland**: It is an approved document for the conservation of fuel and power in buildings. The document consists of four parts L1 A, L1 B and L2 B. Document L1 is specific for dwellings whereas document L2 refers to all other buildings. Part L of the code explains the required values of insulation of the building elements, the permitted sizes of windows, doors and other openings and the air permeability. It sets out the heating efficiency of boilers and the insulation and controls for heating appliances and systems together with hot water storage and lighting efficiency (Guide to Part L of the Building Regulations, 2010). The 2013 edition L1A: Conservation of fuel and power in new dwellings is the current edition for use in England which replaced the previous editions starting from 6 April 2014 (Portal, 2017).

2.3.1 International application of energy standards for buildings

UK & Wales: In the UK, there is an increasing interest among policy makers and researchers in the energy regulations of new dwellings. The Building Regulations (Part L) were revised in 2002, 2006, 2010 and 2013 towards a target of zero carbon in new homes. Part L 'Conservation of fuel and power' deals specifically with the energy efficiency requirements in the built environment and contains four parts: Part L1A for new dwellings, Part L1B for existing dwellings, Part L2A for new buildings other than dwellings, and Part L2B for existing buildings other than dwellings (Portal, 2017). The UK is committed to the reduction of 80% of carbon emissions by year 2050, compared to its levels in 1990. A 25% reduction was achieved in 2010, whilst new buildings are planned to be zero carbon between 2016 and 2020 (Zapata-Lancaster, 2014).

United States: The ENERGY STAR programme is considered as the largest programme in the country defining low energy homes. Buildings certified by ENERGY STAR reduce more than 15% of the energy use compared to similar standard new homes (Tonn *et al.*, 2013). Also, the US Department of Energy introduced a programme in 2008 to increase the adoption of zero-energy domestic buildings in the US. Now, developers commit to delivering new homes that achieve 30% savings on a home energy rating scale (Ward *et al.*, 2011).

Germany: In Germany, the Energy Saving Regulation EnEV defined the thermal insulation standards that need to be satisfied in new buildings and in refurbishment projects. It aims to save heating costs and reduce greenhouse gases, such as CO_2. The energy saving regulations were introduced in 2009 and are referred to as the EnEV 2009. Then, it has been updated to the current version EnEV 2014. The requirements of EnEV 2014 for new buildings are calculated in relation to a reference building with an identical geometry. The standard specifies the envelope properties, such as the U-values and the standard installation for the reference building provided by EnEV. It states that the primary energy use of the proposed building must be below or equal to the energy use of the reference building (GmbH, 2017; Melita Tuschinski, 2017). The aim of the regulation is largely to achieve a climate neutral inventory of the existing buildings by 2050 and around 60% savings in energy consumption through efficiency measures on the building envelope and construction technology compared to its status in 2010 (Energy-efficient building and refurbishment the right way, 2017).

France: The new French regulation RT 2012 issued in December 2012 aims to limit energy consumption in buildings. It came into force for both residential and non-residential buildings in January 2013. RT 2012 defines the total primary energy consumption for heating, cooling, hot water production, lighting, ventilation, and any auxiliary systems used for these purposes. RT 2012 stated the target maximum value of Cep to be 50 kWh/m^{2}a, where the Cep coefficient represents the conventional annual consumption of primary energy of a building, reduced to the floor surface, using the net floor area of the building defined by the French building code (Feldmann, 2013). Furthermore, with the implementation of “RT2020”, buildings’ occupants will be educated to use less energy in order to reduce the energy consumption of their home equipment (Thermal regulations 2012 and 2020 in France, 2017).

Denmark: The Danish building code issued by the Danish Enterprise and Construction Authority, clearly addresses the minimum energy performance required by the code in the form of the primary energy indicator for new buildings. The code, namely BR 10, was amended and updated to the current version BR 15 which has two voluntary low-energy classes named class 2015 and class 2020. These classes represent references for the expected minimum energy performance of buildings in 2015 and 2020. The regulations came into force on the 1st of January 2011. The difference between BR10 and BR08 is that there is a tightening of 25% of the energy performance frameworks and insulation requirements for components and building elements (BR15 in English, 2017).

2.4 Best practice low carbon buildings

Low carbon buildings can be defined as "*any type of building that from design, technologies and operation uses less energy than a similar sized or average traditional building*". In practice this type of building makes use of design, architecture, energy efficient appliances, and landscaping in order to reduce its energy demand. Furthermore, low carbon buildings often use some forms of solar energy to meet its required energy efficiency level. Therefore, the uses of solar energy either in the form of active or passive solar techniques and technologies are very common in LCB (Isiadinso *et al.*, 2011).

The main elements of best practice low carbon buildings include construction methods, materials, regulations, operations and management. Buildings achieve low energy performance through three main strategies: energy demand reduction, use of energy efficient house appliances and the use of renewable energy (Figure 2.1). There are several energy measures that can be implemented in order to achieve a significant demand reduction through design, orientation, construction materials, use of proper shading and the application of insulation (Table 2.2). Whereas energy efficiency in buildings is achieved using rated and smart low energy home appliances that use less energy than regular appliances. Finally, the use of renewable energy sources produced either on site or offsite will reduce the need for conventional energy sources.

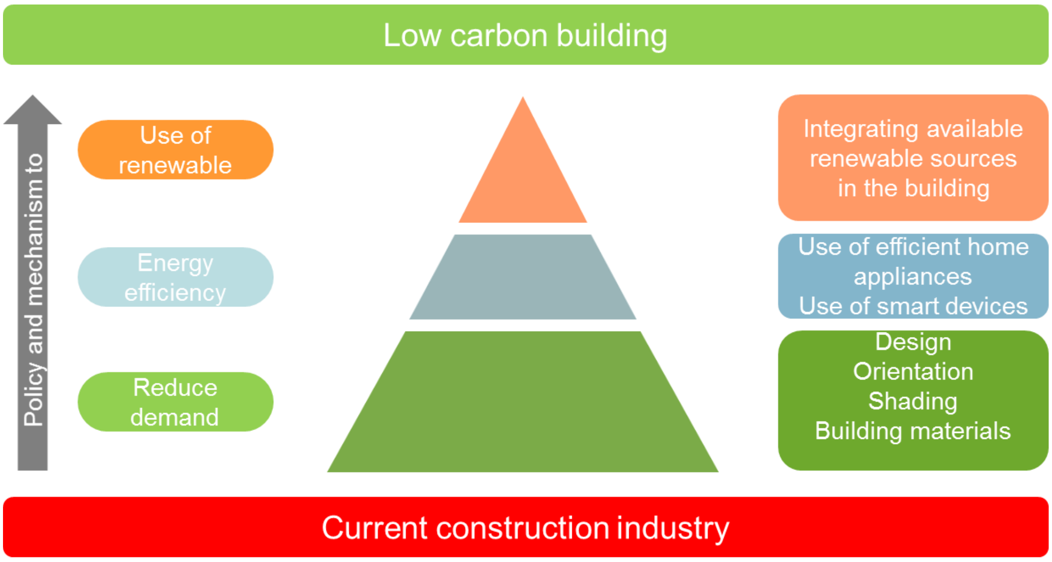


Figure 2.1: Low carbon building hierarchy (Sustainable Approach, 2016)

The role of codes and standards are to act as a roadmap to guide the industry in order to facilitate the application of LCB strategies. It is thus sought to implement a proper technique for a certain condition in order to meet the required goal (Hong, Li & Yan, 2015). In terms of standards and codes, the LCB refer to any house with energy uses below the pre-set demand provided by the standards or building codes. Because energy consumption depends on several economic and environmental factors (Parkin, Mitchell & Coley, 2016), standards therefore vary considerably from one region to another. Thus, in terms of the magnitude of the energy consumed, a low energy building in a country may not be considered as low energy practice in another. In many countries, that aim to limit energy consumption, controlling space heating/cooling is the main target where it represents the largest energy consumer with other energy expenditures, such as lighting. Developed countries, especially in Europe, have established codes, standards and regulations to improve the conservation of energy in buildings mainly targeting the heating of enclosed spaces. These standards are revised and updated continually for more energy efficient building towards the target of zero carbon buildings (Parkin, Mitchell & Coley, 2016).

2.4.1 International best practice of low carbon construction

The need for eco-friendly houses increased due to the adverse effect of conventional buildings on the environment, therefore, the construction of low carbon buildings increased on a global scale. Currently, LCB construction is an increasingly common practice in developed countries such as the UK, where these features have become a requirement imposed by the standard (McLeod, Hopfe & Rezgui, 2012). In many cases, the LCB practice started in research projects and was then implemented in the construction industry. The following is a list of examples illustrating the implementation of best practice in the international construction of low carbon buildings at the time of construction:

1. **Clarum four zero energy research homes at Borrego Springs, California:** This project consists of four homes located in a weather zone similar to the climate of gulf countries. Each house consists of three bedrooms and three baths in a 2,000 ft^2 area of living space, which is similar to the size of a typical residential Omani house area (Figure 2.2). The

Borrego Springs houses are fitted with 3.2 kW photovoltaic solar systems. The homes also have several energy efficiency features in common including tank-less water heaters, rigid polystyrene insulation around the foundation, ENERGY STAR appliances and low energy fluorescent lighting. Heat gain from the sun is kept to minimum through the use of a radiant roof barrier, low-emissivity windows, five-foot overhangs over the homes' envelope, and shade screens on all windows and doors (Zero Energy Demonstration Homes Clarum Homes, n.d.; Case Study: Clarum Homes – Vista Montana, 2007).

Figure 2.2: Clarum zero energy research homes at Borrego Springs, California

(Source: Case Study: Clarum Homes – Vista Montana, 2007)

2. **The Greenwatt Way**: This is a development of homes constructed in 2010 by Scottish and Southern Energy (SSE) (Figure 2.3). All ten homes were designed to meet the May 2009 Code for Sustainable homes (Moving towards zero carbon living, 2017). The project represents a live demonstration for testing small scale domestic heating and the role of occupant interaction with low carbon buildings. The development includes several typologies of UK dwellings, such as one-bed apartments, terraced and detached homes. The project is currently monitored by the SSE and Slough Borough Council staff members, who are participating in the ongoing

monitoring including energy performance and occupant satisfaction surveys (Energi, 2017).

Figure 2.3: Greenwatt Way development (Moving towards zero carbon living, 2017)

2.5 Application of energy standards in MENA countries

The Middle East and North Africa (MENA) region is a geographical region covering the area from Morocco in the east to Iran in the west. The region has many definitions, where different organisations define the region as consisting of different countries and territories (Middle East and North Africa Overview, 2016). In this research, MENA refers to the region commonly defined by the World Bank which includes 20 countries (Table 2.1). According to the UN data, the total population of the MENA region at its least extent is approximately 381 million people, or approximately 6% of the total world population.

MENA countries are facing complex challenges aside from the Arab Spring, including the depletion of natural resources, provision of education and provision of the required energy for future developments (Figure 2.4). For example, based on today's average electricity consumption, the estimated required electricity for housing in Saudi Arabia by 2050 will be approximately 120 GW. Since the main source of energy in Saudi Arabia is oil, this is the equivalent to 8 million barrels of oil per day which is equal to the average current daily production of Saudi Arabia (Husain & Khalil, 2013). This expected high demand of fossil fuel in the future will put a strain on the world energy strategies as MENA is one of the world's largest producers of oil. The demography of MENA is largely similar, therefore, other countries will have an increasing demand for energy especially for housing purposes in a similar manner. In order to meet the domestic energy needs and provide more natural resources, MENA needs to set goals to develop alternative sources of energy, such as, producing energy from renewable sources for a given target. In fact, little has been done to conserve energy in most of these countries. Buildings account for the majority of energy consumption in all of these countries due to a lack of strict building energy laws to help reduce their overall consumption of energy (Meir *et al.*, 2012).

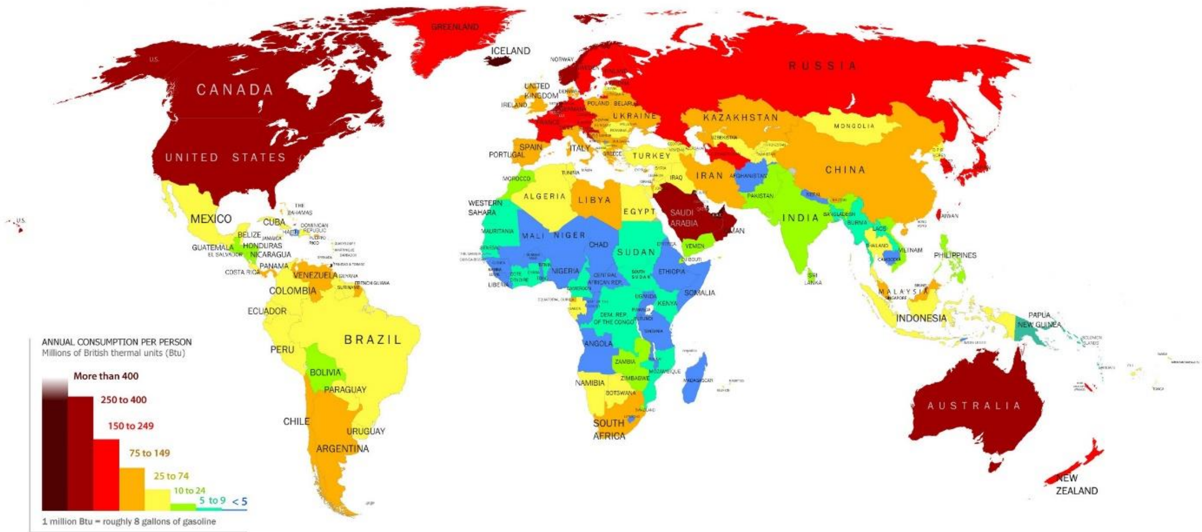


Figure 2.4: Energy consumption per capita per country

(Source: The United Nations world water development report 2014, 2014))

Based on the countries' ranking by energy consumption, apart from Yemen and Sudan, the MENA region can be classified in the medium to high energy consumers per capita. It is well observed that this status reflects a lesser implementation of strategic plans towards sustainability. From this point of view, most of the MENA region including all GCC countries is characterised by the same pattern of energy consumption involving fewer energy standards and high energy use (Table 2.1). However, the application of these standards in each country in the region varies according to their political and economic status. Moreover, from the data presented in the world energy consumption map in Figure 2.4, most MENA countries are considered as high or medium energy consumers per capita. Oman ranked in 10th position in the world and in 5th position in the MENA region (Meir *et al.*, 2012).

No.	World ranking	Country	Energy / capita /year [kgoe/a]	GJ / capita /year	kWh/capita / year	
1	3	Qatar	12799.4	537.58	17041.2	High consumption
2	4	Kuwait	12204.3	512.58	16248.8	
3	7	United Arab Emirates	8271.5	347.4	11012.6	
4	8	Bahrain	7753.7	325.65	10323.2	
5	10	Oman	7187.7	301.88	9569.7	
6	15	Saudi Arabia	6167.9	259.05	8212	
7	37	Libya	3013	126.54	4011.5	
8	38	Israel	3005.4	126.23	4001.3	
9	41	Iran	2816.8	118.3	3750.2	
10	67	Lebanon	1526.1	64.1	2031.8	Mid
11	68	Turkey	1445.1	60.69	1924	
12	76	Jordan	1191.4	50.04	1586.2	
13	78	Iraq	1180.3	49.57	1571.4	
14	79	Algeria	1138.2	47.81	1515.5	
15	83	Syria	1063	44.64	1415.2	
16	86	Tunisia	912.8	38.34	1215.3	
17	87	Egypt	903.1	37.93	1202.4	
18	112	Morocco	516.7	21.7	687.9	Low
19	124	Sudan	370.9	15.58	493.9	
20	131	Yemen	297.9	12.51	396.6	

Table 2.1: Energy consumption per capita per country in MENA

(Source: Reproduced from the data presented by the World Bank, 2013)

2.5.1 Application of energy standards in Iran

In 1991, the Ministry of Housing and Urbanism issued the first building code on energy conservation (Code No. 19). The code was simple and could not be used as a mandatory or system performance method. Then, after ten years, the code was updated to make use of international standards (Riazi & Hosseyni, 2011). The updated version of the code was more specific and introduced two calculation methods referred to as the mandatory method and the performance method. In the mandatory method, which is concerned with small buildings, normally family homes, R in m^2K/W is assigned to each building component. Whereas in the performance method, the heat transfer of a reference building with the same properties of the proposed building is calculated based on the U values determined by the code, and the calculated results should be more than the total heat transfer of the proposed building. Also, the new version of the code included descriptions of the lighting and mechanical systems. Despite the number of codes, Iran paid $84 billion in subsidies for energy in 2008 including residential buildings' electricity (Omrany & Marsono, 2016). Energy consumption data shows that the energy per capita consumption was 15 times higher than that of Japan and 10 times that of the European Union. Similarly to the GCC countries, due to huge energy subsidies, Iran is one of the most energy inefficient countries in the world, with an energy intensity three times higher than the world average and 2.5 times higher than the Middle East average (Fayaz & Kari, 2009; Omrany & Marsono, 2016).

2.5.2 Application of energy standards in Jordan

In Jordan, the building energy code was developed in 2008 by the Royal scientific Society as an update to the 1998 code. It is a voluntary code which covers insulation and other energy applications in buildings based on ASHRAE 90.11-2007. Recently, as part of the new Jordanian national energy efficiency strategy, the use of thermal insulation in residential and commercial buildings in certain zoning areas will be enforced. The strategy also encourages The Jordan Green Building Council to promote appropriate green building concepts and practices for the Jordanian building and construction sector. However, in the real industry there are no energy standards implemented (The State of Energy Efficiency Policies in Middle East Buildings, 2017).

2.5.3 Application of energy standards in Egypt

Egypt developed its own residential building energy efficiency codes between 2005 and 2010. Then, another code was introduced in 2013 to improve the indoor air quality and ventilation requirements. Researchers expect that compliance with the new energy code will have the potential to save approximately 20% of the energy consumption of buildings (Hanna, 2015). However, the new codes are still not compulsory and will be implemented as voluntary requirements. Recent research has also shown that these efforts are yet to make a change in the Egyptian design practices towards an improvement in energy efficiency (Huang *et al*., 2003; Hanna, 2015). Furthermore, the Egypt Green Building Council established in 2009, developed its Green Pyramids Rating System in December 2010. In addition to the development of energy efficiency standards and rating systems, the Egyptian government developed energy labels for the most used home appliances including room air conditioners, washing machines, and refrigerators. Now, it is mandatory for both local manufactured and imported appliances to meet the energy efficiency specifications (Hanna, 2015). The Egyptian Residential Energy Code provided specifications and recommendations for the construction of buildings that aim to provide comfort for the occupants. Although these specifications are well-defined in the code, recommendations for obtaining the best combinations for each climate zone do not exist (Mahdy & Nikolopoulou, 2014).

2.5.4 Application of energy standards in Lebanon

In Lebanon, a thermal energy standard for buildings is under development with the support of the ADEME of France. The Lebanese construction law also provides economic incentives for the voluntary thermal insulation of buildings. However, due to a weak legislative and institutional framework, subsidies of energy prices, and the absence of a national energy strategy, many energy efficiency projects in Lebanon have failed to achieve tangible results (Mourtada, 2008). On the other hand, the Lebanon Green Building Council (LGBC) created the Building Rating System (ARZ), as the first Lebanese green building initiative to implement international standards. It has been established in order to support the growth and adoption of sustainable building practices in Lebanon with a specific focus on the environmental assessment and rating system for commercial buildings. Its aim is to maximise the operational efficiency and minimise the environmental impact. The system includes a list of technologies, techniques, procedures and energy consumption levels that the LGBC recommended to be adopted in green buildings (ARZ Building Rating System, 2017). However, similarly to many other MENA countries, Lebanon's legislative framework remains fragmented and incomplete. The country still lacks comprehensive laws dealing with several energy issues, including renewable energy or energy efficiency. The implementation of the existing legislation remains a major challenge, as the provisions of the existing laws are not implemented. This can be referred to the 2006 July war and how its consequent political difficulties have postponed the implementation of energy codes (The State of Energy Efficiency Policies in Middle East Buildings, 2017).

2.5.5 Application of energy standards in Tunisia

Tunisia has recently implemented both standards and a labelling system for household appliances. As a result of this initiative, it is expected that by 2030 this will save approximately 3.4 Mt of CO_2 emissions (LIHIDHEB, 2007). Law No. 2004-72 defined the conservation of energy as a national priority for the country and will act as the main element of its sustainable development policy. The law referenced three main goals, namely energy saving, the use of renewable energy and the introduction of new forms of construction. Additionally, The National Energy Conservation Action Plan aims to achieve a 30-30 goal, which refers to a production of 30% of electricity from renewable sources by 2030. In parallel with the implementation of the conservation code, the building energy labelling scheme was also developed in 2004. The code and the labelling system became mandatory for office buildings and residential buildings exceeding 500 m^2 in July 2008, with the exception of single-family houses. The code was drafted on the basis of the overall performance of buildings. Whilst the energy rating scale ranges from one to eight and is based on the estimated energy needs for heating and cooling, using the calculation methodology from the building energy code. The reference value in the labelling scheme corresponds to the maximum allowed energy need for the buildings designed according to the current code. Then, this value is set as a reference value of 100% energy consumption for the designed building and corresponds to energy grade 5 in the rating scale. The label system includes three grades below and four grades above this requirement. The lower efficiency grades correspond to buildings which require more energy, that is to say in a proportion of 15%, 35% and 50% than the reference building requirement, whereas the higher efficient grades refer to buildings requiring 15%, 25%, 35% and 40% lower energy rates than the maximum energy requirement allowed by the code (Figure 2.5) (The State of Energy Efficiency Policies in Middle East Buildings, 2017).

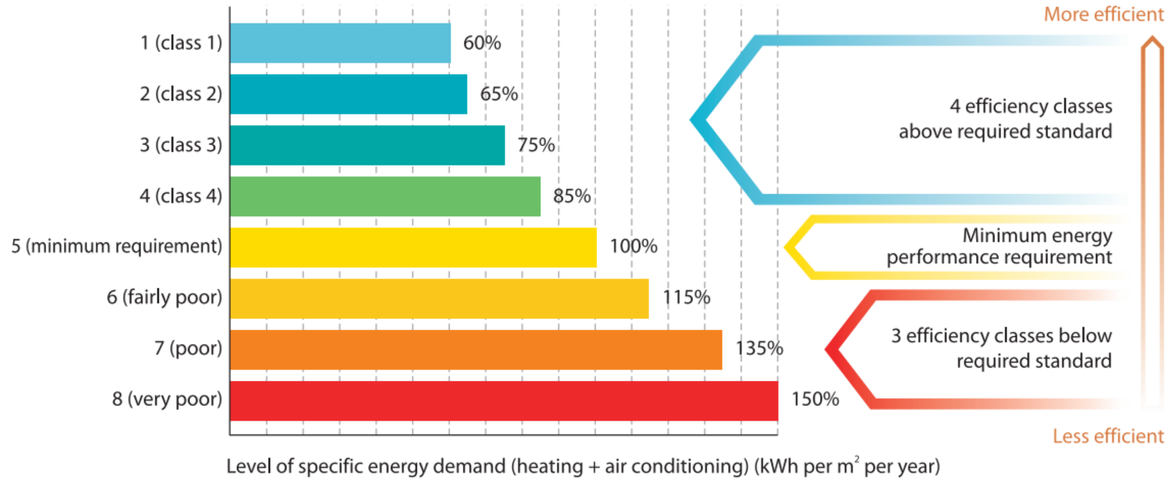


Figure 2.5: Tunisian building energy label

(Source: National Energy Management Agency of Tunisia, 2016)

2.5.6 Application of energy standards in Morocco

Morocco worked to introduce its own independent energy regulations, but the past attempts were unsuccessful due to the complexity entailed by the restructuring of the distribution activities. The government has recently announced its intention to create an independent regulator through the *Agence Nationale de Régulation de l'Energie* (ANRE), which refers to the National Agency for Energy Regulation. However, the available legislations at present are Law no. 47-09 relating to energy efficiency and created on 29 September 2011. This law is considered to serve as reference for the future thermal regulation and benefits from the provisions of both French and German regulations. The regulation aims to increase the efficiency of energy consumption, reduce energy costs on and contribute to a sustainable development (Developing Energy Efficiency Standards and Labelling for Morocco, 2017). Furthermore, it also encourages the application of solar water heaters and energy-saving from lighting applications. Morocco recently set a goal to ensure that 40% of its electricity demand is covered by renewable sources by 2020. This is an ambitious goal considering that more than 90% of its current energy source is imported fossil fuel. In order to achieve these renewable energy goals, Morocco has introduced a legal and regulatory framework for the energy sector (Schinke & Klawitter, 2016). Several legislation and regulatory frameworks have been devised from early 2010 including:

- The Renewable Energy Law 13.09 of February 11, 2010 which aims to foster and promote renewable energy and regulates its commercialisation (reegle - clean energy information gateway, 2014).
- The law for the creation of the National Agency for the Promotion of Renewable Energy and Energy Conservation (ADEREE) of January 13, 2010 (reegle - clean energy information gateway, 2014).
- The law for the creation of the Moroccan Agency for Solar Energy (MASEN) of January 14, 2010, which is the prime contractor for solar power projects (Reegle - clean energy information gateway, 2014).

2.5.7 The MENA LCB status

The current review of the construction process in many of the MENA countries seems to be lacking in energy conservation and environmental initiatives, and the construction of low carbon buildings in particular is still not a common practice. A closer look, however, indicates that the LCB can be considered as one of the key solutions for the area's problems in terms of resource depletion, population growth and urbanisation. This is due to the fact that all MENA countries provide a large amount of subsidies on energy, particularly for domestic use, which will assist in the subsequent development of these countries. According to Meir *et al.* (2012), the majority of MENA countries do not practice energy conservation in domestic buildings or have not established standard yet (Table 2.2).

Among these countries, Oman has not achieved or devised any strategy for adopting a green building standard or introducing any labelling system.

No		Country	Insulation Standard	Energy Efficiency Standard of Buildings	Energy Labelling Standard	Energy Audits Standard	LCB Status
1	Non-GCC Countries	Algeria	U/D	U/D	-	N/I	N/I
2		Egypt	N/I	V	M	V SUBSIDISED	AG
3		Iran	N/I	V - OFFICES	N/I	N/I	N/I
4		Iraq	N/I	N/I	N/I	N/I	N/I
5		Israel	M	V	M	V	Es (Europe)
6		Jordan	M	U/D	N/I	N/I	Em
7		Lebanon	V	V	U/D	N/I	Pr
8		Libya	N/I	N/I	N/I	N/I	AG
9		Morocco	N/I	U/D	U/D	N/I	Pr
10		Palestinian	V	V	N/I	N/I	Pr
11		Syria	V	V	V	N/I	Pr
12		Tunisia	M	M	M	N/I	AG
13		Turkey	M	M	N/I	N/I	Es (Europe)
4		Yemen	N/I	N/I	N/I	N/I	N/I
1	GCC Countries	(Abu Dhabi)	N/I	U/D	M	N/I	Es
2		(Dubai)	N/I	U/D	M	N/I	Es
3		Qatar	U/D	U/D	U/D	U/D	Em
4		Bahrain	N/I	N/I	N/I	N/I	Pr
5		Kuwait	N/I	M	N/I	N/I	Pr
6		KSA	N/I	U/D	N/I	N/I	Pr
7		Oman	N/I	N/I	N/I	N/I	AG

AG	Associated Group	Es	Established	GBC	Green Building Council	N/I	No information
Em	Emerging	GB	Green Building	M	Mandatory	Pr	Prospective
U/D	Under development	V	Voluntary				

Table 2.2: Status of building energy regulations in the MENA countries

(Reproduced from Meir *et al.*, 2012)

2.6 Building energy regulation and policies in the GCC countries

Energy consumption in buildings is a difficult task to control, regulate and measure due to the contributing factors influencing its value. However, the major tasks contributing to the energy regulation in buildings may be evaluated. These are comprised of the lighting heating/cooling and hot water energy consumption. The total energy requirements for these tasks are estimated to be between 65% and 85%. This type of load is referred to as a regulated or measurable load, whilst the remaining is known as an unregulated or unmeasured load (Birchall *et al.*, 2014).

The statistics data from The Cooperation Council for the Arab States of the Gulf Secretariat General stated that by 2020, the total population of the GCC is forecast to be 53.5 million representing an increase of 30% compared to the record total population in 2000, whereas the real GDP is expected to grow by 56% in the next decade. This will provide more potential for development (GCC Statistics, 2017). As the GCC population and developments expand in a rapid manner, the Gulf region faces an increasing strain on its demand for services, including energy consumption for domestic buildings. Furthermore, the regulation of electricity use in domestic buildings, the largest electricity consumers, is still not properly implemented, whereby all GCC countries provide subsidies on electricity. Each country has established a single buyer organisation commissioned to buy electricity from utility companies and resell it to the consumer at reduced costs:

- Saudi Arabia has formed the Electricity and Co-Generation Regulatory Authority (Statistical, 2015).
- Qatar created the Qatar General Electricity & Water Corporation in 2000 (Al-Kuwari, 2017).
- In the UAE, the Abu Dhabi Water and Electricity Authority is a single buyer (About Us – ADWEA, 2017)
- In Oman, the Oman Power and Water Procurement Company acts as a single buyer (The Oman Power and Water Procurement Company (OPWP), 2017).

The UN Agenda 21 (CIB & UNEP-IETC, 2002) stated that the majority of the developing world is undergoing a process of rapid construction. Therefore, sustainable development needs to be better understood in the Gulf countries because of the issues associated with the environmental impact of the rapid construction of buildings, such as health issues, dense urban spaces, and increased energy supply requirements (Sustainable Patterns of Urbanization in Oman | aurelVR architecture, 2014). On the other hand, the increasing population paired with an increased housing demand, the need for more energy, and the limited age of the conventional energy supply, make the issue of energy consumption in buildings a challenging task for the GCC countries. Energy in buildings has become more critical in the absence of government incentives, such as subsidies and grants implemented in order to promote energy efficiency measures and low-cost strategies, such as low carbon buildings that could be implemented in the building sector.

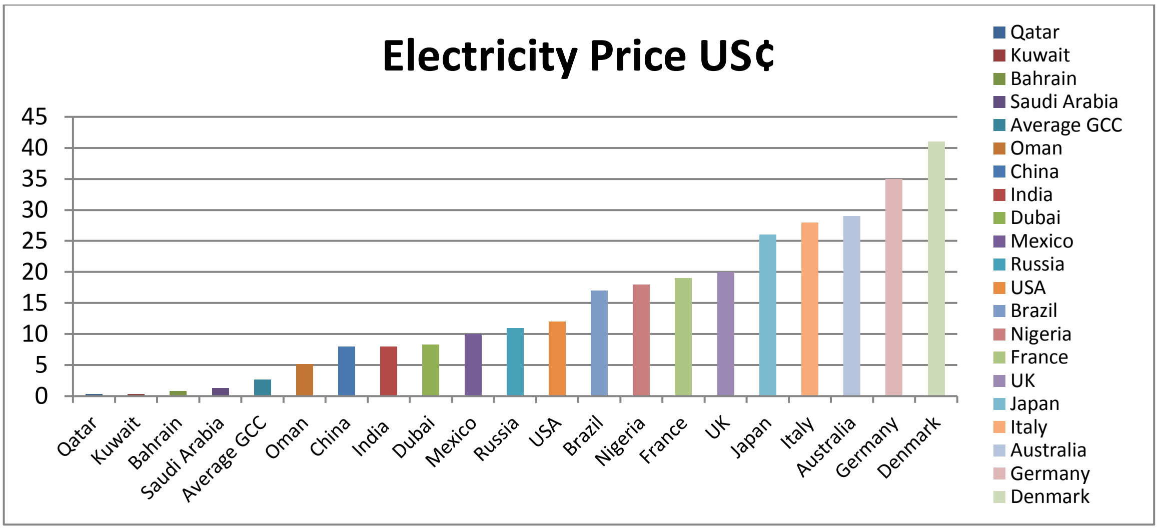


Figure 2.6: Electricity prices in the GCC countries and selected developed countries

(Source: Reproduced from data from World Bank)

Figure 2.6 shows that electricity prices in all GCC countries are very low compared to the international prices. This constitutes one of the major problems and falls behind a reduced implementation of low carbon strategies in these countries.

2.6.1 Status of energy standards in the GCC countries

While building energy standards exist in developed countries, some of the GCC countries are currently introducing such legislation, whereas others have not yet taken any steps in this direction. The GCC Standardization Organization (GSO) of the gulf countries is the main body, which aims to help member countries to achieve various standardisation objectives and follow up on the application and compliance with the standardisation objectives in member countries (GCC Standardization Organization – GSO Technical Subcommittee for Green Buildings, 2017). The organisation consists of two main committees and 21 technical subcommittees in the field of specifications and standards. Committees no. 10 and 11 are the most relevant committees in the field of green buildings. In this regard, subcommittee 10 is numbered as the TC06 Gulf Technical Committee on the specification of construction and construction materials. The task of this technical committee is to prepare draft standards and technical regulations for the GCC in the field of construction materials and activities and to set priorities that meet the actual needs in order to achieve the relevant health, safety and environmental requirements. Conversely, subcommittee 11 numbered TC06/SC01 is an emerging subcommittee concerning the technical specification of green buildings for the Gulf countries. Nevertheless, up to this point, these committees have not yet set up common standards that can be referred to in all GCC countries. Therefore, most members have either created or have started to create their own standards. This is due to the differences in the economic and climatic conditions of each country and the construction visions that each country selected (GCC Standardization Organization – GSO Technical Subcommittee for Green Buildings, 2017). Hence, the building energy standard in the member countries of the GCC is summarised as follows:

Kuwait: In Kuwait, buildings consume 48% of the total energy demand on a national level, whereas air-conditioning accounts for approximately 70% of the buildings' energy demand (Ameer & Krarti, 2016). The latest code of practice for energy conservation was developed to set limits for the electrical consumption of the air-conditioning systems of buildings. The code was developed as part of the Energy Conservation Program referred to as the Code of Practice MEW/R-6/2014. The code introduced energy conservation measures and limits for different types of buildings, but the application of this code is yet to be practically enforced. MEW/R6/1983 is the early version of the energy code for buildings developed by the Ministry of Electricity and Water. The code did not consider any application of thermal storage systems or the thermal insulation of exposed floors. Then in 2010, a new version of the code was issued under the designation MEW/R6/20, as an improvement to the previous version. The new version considered cool storage systems as mandatory for partially occupied buildings. The thermal insulation for exposed floors with an R-value of 10 is mandatory. Moreover, in late 2009, the ASHRAE members from the United States and the Kuwait University created a version of the ASHRAE Standard 90.2-2007 which took account of the differences between the existing standards and the needs of Kuwait. As a result of this cooperation, ASHRAE Standard 90.2 Kuwait, was published in March 2010 and presented to the Kuwait Ministry of Energy and Water (Code of Practice, 2014).

United Arab Emirates: For the last few decades, the rapid urbanisation in the UAE was characterised by forms of imported modern architecture, which is not environmentally responsive to the region's climate. This caused a significant demand for electricity for air conditioning purposes, as can be seen in most major cities, such as Dubai and Abu Dhabi. These unsustainable designs of residential and commercial buildings, in addition to being major consumers of energy, are also massive contributors to the GHG emissions. Therefore, the Government of Abu Dhabi developed a set of measures to reduce energy consumption, including the launch of the Estidama programme and the Pearls green building rating system which was integrated into the building code and became partly enforceable, as well as the launch of the Emirates Green Buildings Council (Estidama – Estidama and Urban Development, 2015).

In Dubai, the latest developments in the construction industry are constituted by the regulations introduced by the Dubai Municipality under Circular No. (198) of 2014 for energy conservation in buildings. In its first publication, the regulations applied to government buildings only. However, from 1 March 2014, the regulations have started to apply to all new construction projects across the residential, commercial and industrial sectors. Furthermore, extensions to and the refurbishment of existing buildings must also comply with the regulations as a basic requirement for a building permit from the Dubai Municipality (Manual of Green Building Materials, Products & Their Testing Facilities, 2017; Green Building Regulations & Specifications, 2015). The primary purpose of the regulations is to improve the energy performance of buildings by seeking to reduce their consumption of energy, water and materials. In order to achieve this, the regulations directly affect all parts of the construction process, from the initial site selection and building design through to construction, post-completion operation and maintenance of the building and finally the removal of the building at the end of its life cycle. When applying for a building permit with the Dubai Municipality, developers are now required to complete a 'Green Building Declaration', defined in the regulations as an "unconditional commitment from the development team to meet the requirements of the Green Building Regulations" (Green Building Regulations & Specifications, 2015).

Moreover, the Emirates Authority for Standardisation and Metrology has launched a scheme in 2010 to certify electronic goods, and air-conditioning units according to their energy efficiency. In 2014, The UAE Energy Efficiency Lighting Standard was introduced as a step taken by the UAE Ecological Footprint Initiative. The standard prevents low-efficiency indoor bulbs from entering the UAE market. As a result of this in terms of energy consumption, it is expected to cut the UAE energy consumption on an annual basis by up to 500 MW (UAE Lighting Standard, 2017).

Qatar: The Ministry of Environment launched the fourth edition of the Qatar Construction Specifications, QCS 2010, specifying a series of measures to pave way for green buildings and gardens in the country and to ensure the safety of construction workers. The Gulf Organization for Research and Development (GORD), the authority for knowledge on sustainability in the MENA region, launched the Global Sustainability Assessment System (GSAS) as the standard for excellence on sustainability in the MENA region as per the 7th of June 2012 (Qatar Construction Standard, 2017). The GSAS looks into various typologies of buildings, such as the Schools Residential Single and Residential Group. The GSAS/QSAS is incorporated within the Qatar Construction Specifications (QCS 2010) in order to provide a clear vision for sustainable building development in the country. The current available version of the standard is referred to as the New Qatar Construction Standards and Practices.

Bahrain: In Bahrain, the energy regulations were started in the 1990s by the National Committee of Buildings in Bahrain (NCBB). In 1997, the government requested the NCBB to provide advice on the conservation of energy in buildings. The committee recommendation was to improve the thermal insulation as the most suitable and practical energy conservation strategy with respect to the current situation of Bahrain (NCBB, 2002). Then, the Bahrain national building codes introduced in 1998 aimed to reduce the electricity consumption within buildings. Additionally, other international codes on building systems and equipment are considered for implementation with respect to energy conservation by the local authority, but there is a serious lack of knowledge and experience that prevent the codes from achieving these objectives. Therefore, in reality there are no existing mandatory or compulsory codes for practice (Radhi, 2008).

Saudi Arabia: The introduction of the Saudi Building Code SBC was effected in June 2000 by a Royal Decree in order to establish the Saudi Building Code National Committee (SBCNC). The SBC was established based on several international building codes from developed and developing countries. The first version of the code approved by the Council was in September 2001, and was made available for practice in 2007 (CA News Network, 2013).

Oman: At present, the only available building code in Oman is the Local Order No. 23/92 Building Regulation for Muscat issued on the 12th of April 1992. The code was later on simplified, consists of four chapters and 134 articles and covers architectural norms, building dimensions and the properties of construction materials. Chapter two covers the architectural and technical conditions of buildings and specifies that the materials used for the building envelope should be non-inflammable and compatible with the local specification in terms of dimensions and properties. Article no 14 stated that heat insulation materials should be used in roofs and external walls if their U value is less than 0.57 W/m^2K and 0.741 W/m^2K. However, the application of insulation in buildings is yet to be achieved. Furthermore, to date, there is no existing standard applying to the conservation of energy in buildings in Oman. Therefore, new buildings are being constructed in the absence of any regulation on energy conservation. The country now seeks to update building codes through its cooperation with the GCC Standardization Organization. However, this cooperation seems ineffective, as most GCC countries work independently and create their own versions. This demonstrates a severe shortage in the current building codes, particularly with respect to the energy conservation in buildings. Hence, the requirement exists to produce modern building codes addressing a framework for the sustainable construction industry in the country.

2.7 Household energy use in Oman: Efficiency and policy implications

According to the World Development Indicators (2012), all GCC countries are listed in the top 20 courtiers in terms of energy consumption per capita per annum. Oman ranked in the 10th position in this list, whereas residential buildings consume 48% of the total electricity produced in the country. Since all residential buildings were designed without considering their energy consumption, most of this energy is consumed for space cooling and comfort satisfaction. A summary of three studies conducted by three different universities in Oman indicates that the annual energy consumption of a household is between 20116 kWh and 37930 kWh (Oman Eco- Friendly House, 2014; Bustan of Oman, 2014; Oman Eco-House Project, 2014). Conversely, a survey of the actual monthly energy consumption for the year

2013 on a total of 100 single family houses of an average size in Oman shows that the average annual electricity consumption is 24757 kWh (Table 2.3).

Month	Modelled electricity consumption kWh				Average measured kWh
	Higher College of Technology	Nizwa University	Sultan Qaboos University	Average	
Jan	1093	2225	1270	1529.333	1086
Feb	935	2196	1150	1427	698
Mar	1304	2766	2090	2053.333	891
Apr	1661	3204	2610	2491.667	1473
May	2289	3911	4370	3523.333	2190
Jun	2409	3875	4780	3688	2863
Jul	2325	3850	4930	3701.667	3022
Aug	2000	3662	4900	3520.667	3424
Sep	1914	3337	4740	3330.333	3035
Oct	1862	3269	3790	2973.667	2805
Nov	1263	2698	2030	1997	1949
Dec	1061	2399	1270	1576.667	1323
Total	20116	37392	37930	31812.67	24757

Table 2.3: Typical Omani house average monthly electricity consumption

The breakdown of the energy consumption by tasks shows that the majority of the total energy consumed on an annual basis is used for space cooling. This can be seen from the high variation in the energy bill between summer and winter. Based on the energy audit conducted on three typical Omani houses in Muscat, for the purpose of this research, the energy use for air-conditioning in a typical summer day is about 78% of the total summer day energy consumption (Figure 2.7). This result seems to be similar in most GCC countries, where researchers from Kuwait and Bahrain found similar values (Al-ajmi & Loveday, 2010; Alnaser, Flanagan & Alnaser, 2008). At present, many researchers expect that the energy consumption in domestic buildings in GCC countries will increase to a greater extent as a result of urbanisation, subsidised tariffs and the increased use of intensive home appliances in the absence of proper labelling systems and energy use regulations. Since the residential sector is rapidly growing in the region, this situation highlighted the need for urgent action in order to overcome the extensive consumption of energy (Al-Badi, Malik & Gastli, 2011; Reiche, 2010; Taleb & Pitts, 2009).

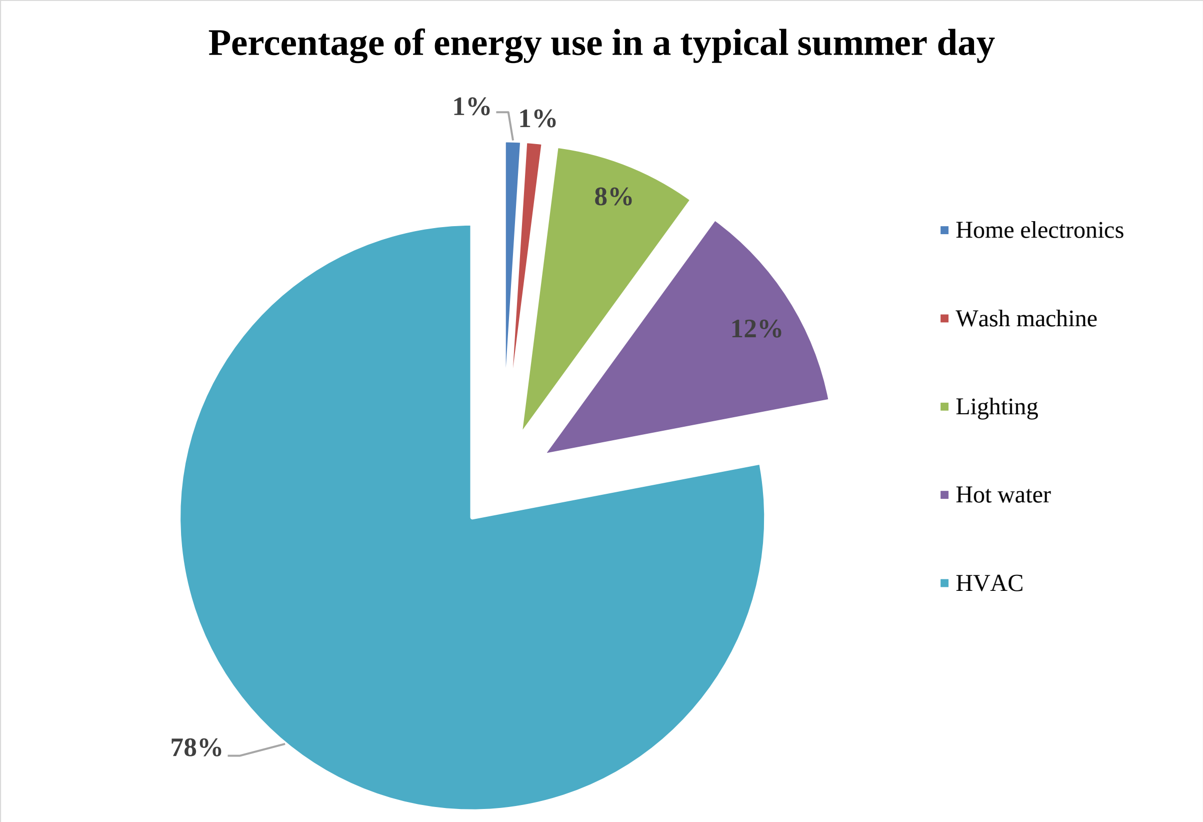


Figure 2.7: Typical Omani house electricity consumption in summer

Source: Energy audit 2014

2.8 Sustainable domestic building construction practices in the GCC countries

The word sustainability comes from the Latin word *sustinere* (to hold; sub, up). Moreover, "to sustain" also implies to "maintain", "support", or "remain". In the Oxford Dictionary the definition for "sustain" is to cause something to continue for a long period of time. Since the 1980s, sustainability has become a more popular word and has been used very often with reference to humans' living activities without a negative impact on the surrounding environment. Hence, if we apply this meaning in the context of the current use of the word "sustainability" it rather implies maintaining the earth's inhabitants for the present and the future. This has facilitated the introduction of the most common definition of sustainability, linked to the concept of sustainable development by the Brundtland Commission of the United Nations on March 20, 1987 and formulated as: *"Sustainable development is the* *development that meets the needs of the present without compromising the ability of future generations to meet their own needs"*. According to Chiu (2012), the definition of the sustainability of housing is: "*The extent to which the environmental impact of housing activities is reduced, thereby conforming to levels which are within the capacity of the natural environment to carry, such that the environmental quality of the surroundings is improved to enable healthy living."* (Chiu, 2012)

In this regard, people's daily living requirements include buildings by utilising available natural sources in a way that will not affect the requirements of future generations with respect to these resources. Traditional building construction is a result of the constraints imposed on the availability of existing resources, whether conditions or financial capacity. Historically, building construction in any region of the world relied on local materials to control the internal environment of the building to a comfortable environment in a sustainable manner. This has happened in the preindustrial period without modern means or often extraordinary energy sources (Thomas, 2002). A notable change in the course of civilisation was triggered by the Industrial Revolution, which first started in the UK in the 17th century. One of its distinguished features was a shift in the sources of energy from wood to fossil fuels, which subsequently altered human activities in many ways and also exerted an impact on the construction industry. After the industrial revolution, and with the development of modern cement in the 18th century, the construction of buildings became an unsustainable industry, as it consumed large amounts of energy and resulted in increased CO_2 emissions. In the 20th century, construction materials used include more energy intense products such as aluminium, glass and industrialised fabric. This has raised the need for an increased awareness in the sustainable construction industry.

The traditional building construction in the gulf countries was a result product of the interaction between the environmental factors (site, geography, topography, and climate) and the social and cultural constrains (religion, traditions, norms, and cultural background). In the pre-oil era, people in the gulf area lived in buildings that modified temperatures and provided natural ventilation with zero environmental impact. It is well known that the climate was a major factor in the formation of the gulf's traditional architecture, where several responses to the climatic conditions could be found in traditional buildings such as court yard houses and Arish (houses built from palm tree and leaves (Figure 2.8). Tents were the traditional home for the Bedouins in the desert, and stone houses with openings close to the roofs were the popular housing option in the mountains. The materials used in the construction of buildings in the past were mud, limestone, gypsum, stones and tree palms. All these materials were classified as sustainable materials, as they did not have any negative impact on the environment. Such effective solutions had come from the environment, and will still be applicable in the case of the local environment and the available materials rather than transforming and dominating solutions (Battle & McCarthy, 2001).

Figure 2.8: Tree palm house (Arish)

During the past 40 years, the GCC was characterised by a rapid development that introduced a modern lifestyle to the region. The new luxurious lifestyle entailed high energy demands which were almost entirely dependent on fossil fuels. Issues such as climate change, biodiversity loss, environmental pollution, desertification, deforestation, proliferation of natural disasters, water and air pollution, are some of the direct consequences of this fast development. Until recently, most buildings in the Gulf States are designed and built without any consideration being paid to the energy consumption and its side effects on the local environment. Today, as a result of the global dissemination of a modern international style of buildings and a new trend related to modern buildings, tall glass façade buildings are constructed in cities such as Dubai, Riyadh, Abu Dhabi, Doha, and Manama without considering the heat gain of buildings due to this type of material. This strategy was normally applied with the purpose of increasing the solar gain in order to heat up buildings, and utilise daylight. Generally, this strategy is often used in cold climates in order to reduce the energy used for the heating load of the building. However, in hot climates, such as those of the GCC, using this strategy may lead to increased energy consumption with respect to the cooling load. The high consumption of energy for cooling buildings in the Gulf region due to building design and materials incentivises architects to pay more attention to the energy performance of buildings, especially with respect to the right selection of construction materials to make the construction industry sustainable again.

2.9 Vernacular construction practice: materials, methods & exemplars

The word “vernacular” has different meanings depending on the context of its use. This term is used by architects, archaeologists, folklorists, historians and other specialists. It is derived from the Latin word “*vernaculus*”, which means "native". In architecture, it is defined as the science of building (Oliver, 2006). Hence, the general meaning of the term vernacular architecture can be translated as the native science of building. From an architectural point of view, vernacular architecture is the process of designing and building a dwelling by people for people to meet the specific needs for comfort or utility and functionality in the building. The use of local building materials and ideas inspired from the surrounding environment are the key elements of vernacular architecture, which sustain it over an extended period of time. Today, vernacular architecture refers to building new structures based on old techniques, shapes or model while at the same time including traditional attributes. Moreover, the vernacular architecture refers to the efficient use of resources within a climate responsive design. The vernacular architecture is a result of several factors to provide acceptable living spaces to the occupants through the selection of a suitable living pattern, building designs and materials. In Oman and the GCC countries, the important factors affecting the construction practice are the weather conditions and the social factors including religions and norms where all the native population comes from an Arab Muslim background. Before the oil era, the economic and social factors of all GCC countries were the same, therefore, building types differed based on the topography and climate conditions of the region. These considerations and a limited possibility to import construction materials from overseas directed the construction practice to a specific technique and methodology to provide a comfortable thermal performance of buildings in the absence of energy sources. These considerations are deemed as the main drivers of vernacular architecture in terms of providing living spaces that are thermally acceptable.

Oman’s topography, the location and the area of the country create a variation in the climatic categories, which have influenced the prototypes of the Omani vernacular architecture. Most of Oman’s populations are concentrated in cities located in the coastal regions, where the climate is mostly moderate in winter and hot humid in summer. In addition, there are number of population settlements located in the mainland region that have the same winters but hot dry summers, whereas very a limited portion of the population live in the mountains where the climate is relatively cooler in winter and moderate in summer. Based on this, and for the purpose of this study, the vernacular architecture of Oman can be classified into two main categories: the costal type of buildings, and the desert and interior type of buildings. The main features of these building typologies are:

1. In the coastal regions, buildings were built from materials that could moderate the amount of transmitted moisture and the building design exploited sea breezes to improve internal thermal comfort. Such houses can be found in the coastal cities of Oman, for example in Sohar, Muscat and Sur, where the land/sea breeze is a local climatic phenomenon. Since the natural air movement is an important mechanism to achieving thermal comfort in this climatic condition, houses were designed to utilise this breeze and direct it into the inhabited spaces of the buildings (Al-Hinai *et al.*, 1993).
2. The desert and interior type of buildings were influenced significantly by the topography of the impressive mountain range and the arid desert located at a distance from the sea. With this type of climate and topography, the diurnal and annual local ambient temperature fluctuations generally exceed those experienced on the coastal. Therefore, in these regions buildings’ walls were constructed from mud and stones with a thickness of more than 500mm. This type of building can be seen in mainland Oman in cities such as Nizwa, Ibri and Buraimi (Al-Hinai *et al.*, 1993).

Nowadays the vernacular architecture of Oman disappeared due to several reasons. As a direct result of ignoring traditional construction patterns, current residential buildings tend not to consider the energy consumption involved. According to Al-Hinai *et al.* (1993), this has happened due to a misunderstanding of Oman’s vernacular architecture by the foreign architects and labourers who participated in the early stage of the country developments. In addition, Al- Hinai argued that modern concrete buildings tend to be more hygienic, easy to clean and require less maintenance, which make better options for clients. Furthermore, one of the major reasons behind the disappearance of the local vernacular architecture in Oman is the lack of building regulations that adopt the use of local architecture in the current construction industry. Despite the fact that the building regulations stated that the construction of buildings in Muscat should follow the local Arab Islamic design, in reality, a traditional building methodology is adopted in the appearance of the building without considering the energy performance of new buildings compared to vernacular constructions. Hence, the need exists to review building regulation and practice in order to benefit from what has been achieved by the past construction industry. Nevertheless, the vernacular architecture of Oman may not be able to provide a level of thermal comfort as well as modern technology does, but some of its techniques can be integrated into the modern construction industry to reduce energy use in buildings through benefits from the past experience applied to future constructions.

2.10 GCC current construction practice

Nowadays the construction industry in the Gulf countries is one of the largest expanding sectors with an annual worth of more than $5 billion involving more than 2.7 million companies of various sizes (Construct Arabia, 2012). The construction industry is growing rapidly, and these countries are facing a continuous demand for housing, especially in major cities. This is due to the rapid increases in population and the expanding oil industry sector that attracts many people to migrate to these cities (Al-Mulla, 2013). The continued demand for housing units has resulted in a shift to new methods of construction in the industry in order to sustain its ability to construct the required buildings. Therefore, building designs, materials and methods of construction are influenced by the construction practices of modern industrial countries. In some cases, low rise buildings have been replaced by high rise buildings in order to overcome the rapid increase in the required housing units. According to the data collected from the Skyscraper Centre, 23 of the top 100 tallest completed towers in the world are located in GCC countries (at the time of writing this thesis) (100 Tallest Completed Buildings in the World - The Skyscraper Centre, 2017). Consequently, the construction of new dwellings has increased at a high rate and this rate may remain the same for the next few years since the rate of the population growth is increasing. According to the census data in Oman, residential building construction permits increased from 18,230 to 33,264 between 2010 and 2012, accounting for an increase of 55% over the course of two years.

2.10.1 Modern construction

Modern construction in the GCC countries practically began in the 1930s with the beginning of the oil era. The modernisation process accelerated in the 1950s and 1960s, when the oil industry attracted international companies to the region as a future source of energy and for its potential opportunities of investment. These issues enhanced the widely adopted visions of the GCC countries towards the future and their persistence to be in the same modern levels with the industrialised countries (Al-Zubaidi, 2007). The general tendency of people in the GCC is to seek larger floor spaces especially under a generally increasing income. Therefore, with the increasing trends in floor space, the energy demand associated with buildings is also increasing, which highlights the need for solutions to overcome this rapid increase in energy consumption. Reducing the energy demand of buildings not only reduces the energy consumption and subsequently the energy cost, but it also improves its value in the property market. As it has been mentioned in the previous section of this chapter, the construction practice in GCC countries was affected by the social environmental and economic constrains. Nevertheless, the social and environmental constrains have not been changed before and after the oil era, whereas the economic factor changed dramatically. The significant amount of money gained from the oil industry provided a significant change which accelerated the transition of the local construction industry towards a modern industry. Consequently, the construction technique has developed to meet continued requirements, such as the load bearing wall system being replaced by a steel/concrete column and beams system, known as the frame structure. The growing rate of urbanisation has resulted in a higher demand for new dwellings and land prices have increased significantly. This has resulted in the building market applying cheap modern ways of construction to optimise land use and be able to construct buildings faster and at reasonable costs. Currently, a typical residential building in Oman is made of a reinforced concrete frame structure and concrete blocks walls. The outer skin of the building is usually made from concrete and consists of a single layer of blocks (100 - 200 mm wide) covered by a 10-25 mm layer of plaster. The roofs are normally flat reinforced concrete slabs covered by waterproof tiles. The thermal performance of most of these buildings is relatively poor, and characterised by the absence of thermal insulation. The energy consumption for cooling purposes in these buildings is relatively high because of a lack of consideration being given to the use of insulation in order to avoid heat gain.

2.10.2 Effects of the current GCC construction practice on the energy consumption

It has been recognised that all GCC countries experience high energy consumption in residential buildings and these findings have been ranked in the top 20 list of CO_2 emissions per capita. Energy efficiency improvements in residential buildings and the implementation of sustainability codes and regulations are the most effective methods used in order to reduce energy consumption and its associated CO_2 emissions. Rapid developments and the current state of the modern construction industry neglected the local traditional architectural solutions provided by the vernacular architecture in order to solve the current energy consumption challenges that face the built environment in the region. Instead, modern technology solutions have been implemented, which usually require energy in order to solve the problems, and as a result, this created a cycle of unsustainable developments. This has created a separation between past and present built environments and raises concerns for a sustainable future.

As a result of the unsustainable construction practice in the GCC countries and unregulated energy use, the energy consumption and CO_2 per capita increased. Now, the energy consumption in the residential sector in GCC countries represents 48% to 52% of the total energy consumption while this is estimated to be between 30% and 35% in the industrialised countries. The energy consumption per capita increased in the past four decades and is predicted to continue to increase under the same conditions. The electricity demand increases every year by 8% compared to the international average of 2% (Ibid, 2014). This shows an increasing gap in people's life between past and present in terms of sustainability. According to the report presented by the Economist Intelligence Unit (2012), the energy consumption per capita in the GCC countries is considerably higher compared to the industrialised countries. It is almost more than double its value in Germany and more than seven times the value in China. Moreover, it is increasing and expected to increase in the future under the same conditions (Figure 2.9).

Figure 2.9: Energy consumption of the GCC and selected industrialised countries

(Source Economist Intelligence Unit, 2012)

2.11 GCC low carbon building practice status

The energy consumption of building sector in all GCC countries consumes more than 48% of the total electricity generated. In addition, the rate of urbanisation and the construction of new dwelling remain at a higher level. This provides a need for a low energy building pathway that aims to reduce the overall energy consumption at a national level. In the GCC countries, in order to eliminate the sequences of an overuse of energy in domestic buildings, various policies have been developed since the year 2010.

Recently, the focus of GCC countries gradually shifted to improving the construction standards and quality of building construction with the purpose of reducing energy consumption. GCC governments aim to take serious decisions to tighten building regulations so as to ensure that the construction industry is concerned with sustainability and energy usage. The UAE and Qatar began have made significant progress in this respect toward implementing regulations and developing sustainability building codes. While Saudi Arabia is in the process of adopting building sustainability codes, a low energy construction has practically not started in Bahrain and Oman.

In this regard, local governments in the GCC have shown some interest in terms of promoting low energy buildings. Examples of these major steps are the construction number of LCB in the UAE and Qatar, such as Masdar City as a project for a carbon-neutral and Energy City Qatar (ECQ). However, energy efficiency regulations and energy saving practice in domestic buildings are still lagging on an international level, which indicates that there is still a need for updating existing regulations. Furthermore, in some GCC countries, knowledge about the performance of regulations and policies is still required in order to encourage more energy efficiency in buildings, whereas other GCC countries such as Oman have not yet started to develop a policy for energy in the residential sector. In fact, there is a need for further 'policy development' in order to gain experience about the regulation of energy efficiency in buildings and their practice before the full establishment of such policies.

2.11.1 Examples of low carbon building construction strategies in GCC

A number of low carbon building projects have recently been established in most GCC countries. GCC governments have greatly placed their support to start energy efficient construction because of the existing opportunities in the region for energy saving and green development. In 2014, a report by Ventures Middle East mentioned that *"Green buildings witnessed a slow take off in the GCC,"* but local governments acted positively in the past four years to embrace sustainability through education and legislation. However, the construction of LCB residential low carbon buildings remains inactive due to a limited awareness in the local community. In this respect, the interest in effective low energy buildings remained limited to government and semi-governmental buildings. Examples of the most energy efficient buildings in the GCC countries include:

1- King Abdullah Financial District. Tadawul Tower 40-storey tower totalling to 140,000 m^2 plus a three-storey car park. Designed to achieve a Leadership in Energy and Environmental Design (LEED) rating Started 2010.

2- King Abdullah University of Science and Technology (KAUST), a new international graduate-level research university with a 12 km^2 desert campus located in Thuwal, Saudi Arabia. Designed and built by developer Hellmuth Obata Kassabaum, Dubai (HOK) in less than three years, completed in 2009. KAUST (up to date) is the world's largest LEED NC-Platinum project.

3- Dubai Smart Sustainable City is a 14,000-hectare residential development, shaped like a desert flower, has 20,000 plots for the UAE national citizens. The roofs of the homes and buildings are designed to be covered with solar panels, which will provide 200 MW of electricity. The city is expected to produce 50% of its own energy when completed in 2020 (Kapur, 2014).

4- DEWA's Sustainable Building is the largest government building in the world to secure a LEED Platinum rating for green buildings in 2013. Green features help the building to reduce its energy consumption by 66%. In addition, 36% of the construction material used was recycled content (Staff, 2013).

5- Msheireb, Doha is the world's largest collection of LEED certified buildings. The 31-hectare town of Msheireb in the centre of Doha the capital of Qatar incorporates the latest and greatest green design elements while accommodating traditional Arabian architecture. The new town will include retail spaces, hotels and apartments. More than 70% of the project will be completed by year 2016 with a total cost of US$ 5.5 billion (Latest News - Msheireb Properties, 2017).

6- The Qatar City Education Convention Centre in Doha is a project which spans across an area of approximately 185,806 m^2 and costs $720 million. The convention centre's roof has been designed to support over 353 m^2 of solar panels. The solar panels are expected to produce approximately 12.5% of the project's energy (Frearson, 2013).

7- Bahrain World Trade Centre (BWTC), Bahrain: Built in 2008 and designed by Atkins, the BWTC is a landmark building overlooking the Manama waterfront. It is also the world's first skyscraper with wind turbines within its structure. The wind turbines are designed to provide between 11% and 15% of the energy consumption, or approximately 1.1 to 1.3 GWh a year. The three turbines were turned on for the first time on 8 April 2008. They are expected to operate 50% of the time on an average day.

2.11.2 Omani examples of domestic LCB: Case study buildings

During the past few decades, Oman has not shown any interest in low energy buildings and reducing global warming. Therefore, the construction industry has not paid any attention to the construction of low carbon buildings. Nevertheless, recently, the construction of low carbon buildings has begun to gradually emerge in the country. This has happened in the absence of a clear government policy and regulatory framework.

The first LCB constructed in Oman was the Majan Electricity Company (MJEC) which had been planned for construction in 2008 and became ready for occupancy by January 2013 (Figure 2.10). This five-storey, 3,000 m^2 building, of 600 m^2 on each floor was designed to utilise concepts and methods that will conserve the energy uses in buildings. The building has chilled water pipes running between the concrete slabs and the false ceiling in each floor for cooling. The building envelope is made from a double concrete block wall and double glazed windows with an insulated roof covered by 50kW PV panels expected to generate a 15% saving of the conventional energy consumption and promote the awareness about low energy consumption locally. Also, it is designed to include vegetation that will generate 20 tonnes of oxygen and reduce 20 tonnes of CO_2 produced by the building per year (Newspaper, 2011). However, the building solar panels were placed without considering the wind effects in the site; therefore, they have been removed in 2016 for safety purposes.

Figure 2.10: Majan Electricity Company building

Furthermore, another step has been taken to encourage the development of LCB construction practices in Oman. The research Council TRC organised the first Oman Eco-House Design Competition, which is accessible to all higher education institutions offering programmes in engineering, design and architecture. Each team is instructed to design, build and operate a house that is an energy efficient building.

Five participating teams were qualified for the final stage of the competition and their design has been approved for construction by the TCR (Table 2.4). These five teams are: Dhofar University, the German University of Technology in Oman (GU tech), the Higher College of Technology University of Technology in Oman (GU tech), the Sultan Qaboos University and the University of Nizwa.

	Name of Project	**Team**	**Location**	**Total Built Area (m^2)**	**Building**
1	Dhofari Eco-House	Dhofar University	Salalah	324	
2	GUTech Eco house	German University of Technology in Oman (GU tech)	Al Seeb	257	
3	HCT GreenNest	Higher College of Technology	Bosher	287	
4	SQU House	Sultan Qaboos University	Al Khod	354	
5	BUSTAN OMAN	University of Nizwa.	Nizwa	354	

Table 2.4: Examples of state-of-the-art residential LCB buildings in Oman

The teams employed various strategies to increase the energy efficiency and reduce the energy consumption of buildings. Among these techniques, traditional Omani mud bricks, solar panels, natural ventilation and double glazing were used in the construction of these buildings. Despite the steps being taken to start a low energy building culture, the number of available projects is very limited and not evaluated to assess the real benefits of these projects.

2.12 Energy efficiency labelling of buildings

The World Energy Council stated that labelling and the minimum energy efficiency criteria are among the top performing options for a fast improvement in energy consumption. Therefore, it is considered as an effective tool in reducing energy consumption in residential buildings. For more benefits from a labelling system, it requires to be set to a performance goal through a mechanism that includes both the consumer and the domestic market to encourage both to provide more energy efficient home appliances. The energy efficient labelling of buildings is a technique to ensure the conservation of energy during the operation stage. Household appliances labelling can have significant impacts on reducing the overall energy consumption if they meet the requirements as per the design. However, if home appliances are not rated, they may lead to a higher consumption of energy than planned in the design stage.

The labelling of residential buildings is a system used to provide information on the overall energy performance of buildings (Figure 2.11). The objective of labelling is to raise awareness and to provide occupants with the classification of the energy use of the building compared to the general ranking system. A good example of building energy labelling is the system used in the UK established as per the requirements of EU Directive 2002.

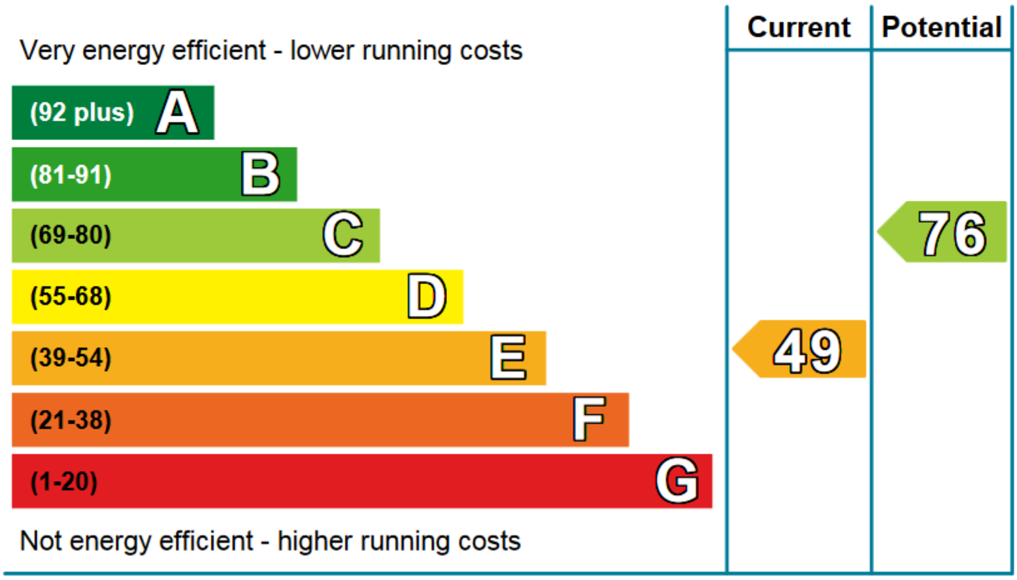


Figure 2.11: Building performance in England and Wales

(Display energy certificate DEC, 2017)

Many rating programmes have been developed to help non-specialists to easily appraise the energy efficiency performance of a building and mobilise them in favour of energy efficiency. These ratings can be used by several different types of actors, such as potential buyers, renters, or occupants, financial institutions and governmental agencies. Recently, some of the gulf countries, such as Saudi Arabia, established a labelling system for home appliances, whereas the Abu Dhabi Urban Planning Council included the labelling of buildings appliances as one of the requirements of its Building Rating System in the section resourceful energy, part RE-3 (Energy Efficient Appliances of Buildings). RE-3 stated that *"an appropriate level under a comparable rating scheme provided the appliance meets or exceeds equivalent level requirements under the Energy Star or EU Energy Efficiency Labelling Scheme can be used to satisfy pearl rating system."* However, Oman has not started any policy to develop any system of energy performance labelling or any public awareness programme at this stage.

2.13 Deficiencies of LCB practice and strategies in Oman

Buildings are a key contributor to climate change and have the largest and most cost-effective mitigation potential. Buildings consume about a third of the total global final energy demand and are responsible for about 30% of the energy-related CO_2 emissions worldwide. Hence, buildings have the largest low-cost climate change mitigation potential. Residential buildings in Oman consume 48% of the total energy demand on a national level and thus the residential sector is one of the main sectors responsible for country's high CO_2 emission ranking. Despite this tremendous opportunity to significantly decrease the consumption of energy and emissions in buildings, there are limited studies that rigorously quantify the potential of reducing the adverse effects. More than 50% of the residential buildings in Oman were built after 2004, whereas the current construction practice in the country shows an inexistent to a more limited implementation of practical LCB in the construction industry. According to the Oman Chamber of Commerce and Industry, there are more than 700 companies registered in grade one and excellent in the construction sector (Said Meselhy & ElSaeed, 2016). These companies pertain to the concrete based construction practice. In 2008, the first Rapidwall building was constructed by one of these companies as a new promising construction method that could reduce the building's energy consumption. Rapidwall consists of fibre reinforced gypsum panels made in a factory and transported for erection in the site. This construction method was first initiated in Australia in the 1990s, and it was then used in China and India (Rapidwall, 2009). However, in Oman, its use is mainly limited to government projects. This demonstrates a lack of strategies to increase the adoption of low carbon buildings in the country.

2.14 Barriers facing the building energy regulation application in the GCC

The application of energy regulations will be one of the biggest threats to the GCC's sustainability development because of the nature of the local society and the dependency of the energy sector on subsidised fossil fuel. The application of the energy regulation will be a real measure for successful energy efficiency policies. The objective of the energy efficiency regulations in buildings can only be achieved by the efforts of all parties including the construction industry, public, governmental authorities with a continuous R&D on the energy performance of buildings, which is suitable for the gulf region climate. Hence, the barriers associated with different parties' expectation will tend to prevent the application of energy regulations. Therefore, a study specifying the relationships between all parties with reference to these barriers to energy regulations will be conducted in this research.

2.15 Benefits of applying energy regulations in domestic buildings

Globally, buildings account for up to 40% of the total end use of energy. Given the availability of many possible strategies to substantially reduce the buildings' energy requirements, the potential savings of energy efficiency in the building sector would lead to numerous benefits. Since the scale of energy use in buildings is large, it will positively contribute to climate preservation, public health, and the protection of the economic growth environment on a both national and a global scale. Reducing the building energy consumption in GCC countries can increase the amount of exported oil, which will be reflected positively on the countries' economy. A moderation of the energy-end use in buildings will also reduce the greenhouse gas emissions and pollution produced from the combustion of fossil fuels. Compared to conventional buildings, energy efficient buildings offer a more stable indoor climate. As households demand less energy for building-related uses, doubling the potential is expected to improve the environment and public health (Figure 2.12).

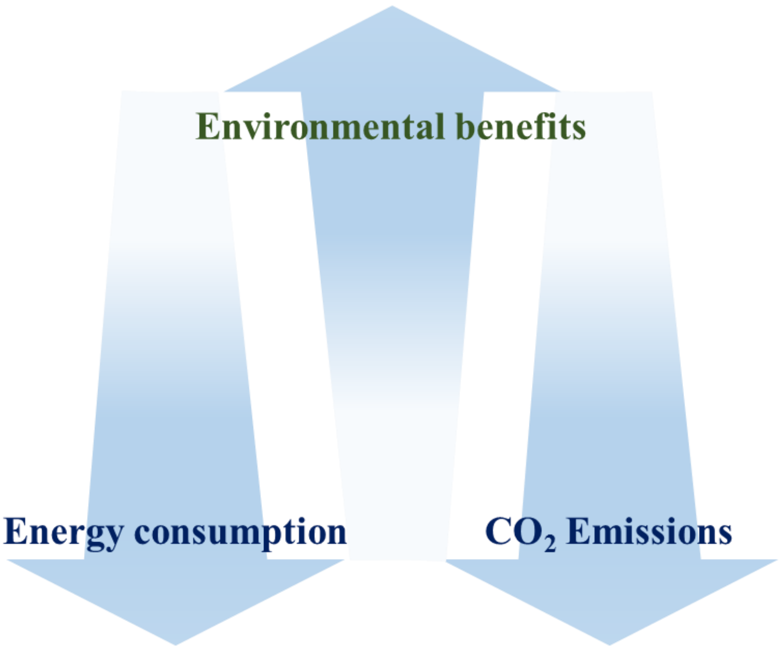


Figure 2.12: Relationship between energy consumption, savings and CO_2 emissions

2.15.1 Environmental benefits

It is expected that within a period of 40 to 200 years, most non-renewable natural resources, such as oil, natural gas and coal, will be consumed if they are not managed in a sustainable way (Ting, Mohammed & Wai, 2011). The availability of natural resources in any country will be reflected in economic prosperity and a better lifestyle. Oil, for example, has facilitated the transition of Oman from rural scattered areas to a modern urbanised country. However, based on the current production of oil and available reservoir in Oman, the production will last for only 20 years. The conservation and management of natural resources for the sake of future generations is the main concept that is common among all the definitions available for sustainability. Hence, the preservation of natural resources can be achieved through the application and adaptation of a sustainable construction industry. Developing countries have the advantage of applying the concepts and applications of sustainability while projects are still undergoing development. Oman is an example of a developing country which will benefit from the country's natural resources in the future if it endeavours to apply sustainability in the built environment at this stage. The benefits earned will include air quality deterioration in urban areas, high energy demand and consumption due to regional population growth and economic development, concerns about safe drinking water supplies due to a scarcity of fresh water, industrial pollution, waste management, pollution in coastal areas; and subsequent stress on the marine ecosystems.

2.15.2 Impacts of energy conservation on building design

The architectural design of a building is the concept in which it will operate and function, and thus the better the design considering the functionality of the building, the better the outcome. Considering the energy consumption of buildings in the design during the early stages along with the multi-disciplinary aspects thereof, constitutes the work process of the architect. The architectural design process and more specifically the early design stages, embrace major opportunities in achieving low carbon buildings. During the early design stage, the important parameters affecting the building performance are addressed. Hence, a modelling aid will be required to achieve optimal efficiency in the design. Tasks, such as form finding should include environmental performance and energy efficiency aspects, such as space layout, aesthetics and natural ventilation. Hence, the sizes of spaces, layout, orientation and opening sizes will be considered to achieve more energy efficient buildings. In addition, with respect to the low carbon design, the design should consider construction materials to enhance the performance of the building. The adoption of properly available sustainable materials will be counted in the overall energy budget of the building. The application of these energy measures was made possible by looking at state-of-the-art LCB in Oman compared to conventional buildings.

2.15.3 Impacts of energy conservation on building materials

A building consisting of a building envelope includes external walls and roof and partition walls separating the internal spaces. The building envelope in the gulf forms an effective barrier against the extremes of the external climate. It provides filtering that modifies the climate sufficiently for the internal conditions to be more acceptable. It acts as a passive modifier to the external climate, depending on the characteristics of each material and their arrangement determines the way the external climate influences the internal conditions (Collier, 1995). Therefore, building materials need to be selected carefully to provide comfort conditions in the building interior and help in reducing the energy consumption in the building. Thus, the use of insulations, low heat transfer material and glazing are highly required in a hot climate.

2.15.4 Feasibility of domestic low carbon buildings in the GCC

The application of LCB measures in housing will reduce the overall costs of the lifecycle of the building. Low-carbon buildings can achieve up to a 70% reduction of the operation energy, which will positively contribute to the reduction of the overall cost of the building. Moreover, energy efficient housing achieves environmental benefits that will add further values to its overall costs. However, the critical question is the affordable housing that can achieve these benefits based on the current energy and construction market will be. Affordable housing units, according to Smith (2012), are *'dwellings built specifically for those whose income denies them the ability to purchase or rent on the open market'*. Another important question is up to what extent the construction market can apply sustainability features based on its current technological ability.

2.16 Chapter summary

As this chapter shows, the building sector can contribute significantly to mitigating climate change, while delivering many other societal benefits. For the building sector to act positively in reducing the energy consumption of a country, the energy efficiency code for a building is required in order to ensure that said building uses less energy while achieving the required function. However, the good policy requires good knowledge about the status of building performance.

While the MENA and GCC countries have a different LCB status, there is a gap in knowledge and insufficient literature to cover the adoption of low carbon buildings in Oman. This demonstrated that this area requires further investigation to evaluate the current options of low carbon buildings in terms of the building energy performance and comfort to provide guidelines for future sustainable buildings. Additionally, more research is required in order to assess the society and industry support for a paradigm shift towards low carbon buildings, and establish a preference benchmark for the energy use of a building based on the building area and the number of occupants that can be referred to when evaluating the energy consumption.

2.16.1 Identified gaps in knowledge

It is clear that there are some specific issues and challenges facing the development and implementation of sustainable housing in Oman. This is more particular to the current time as the traditional vernacular style of architecture proved to be sustainable in the past in multiple ways, at a time before the term sustainability was included in our vocabulary and building designs. Today, housing in the Sultanate of Oman has transitioned from a traditional local society to new and advanced housing units, prompted by the use of modern architectural construction methods and design styles similar to those in many developed societies. In addition, Oman is naturally afflicted by a harsh arid climate and a high consumption of non-renewable natural resources. The building construction sector is the main energy consumer in the country as it consumes more than 48% of the total delivered electricity. This has happened as a result of absent strategies and codes for low carbon buildings. Currently, the construction industry in Oman is lagging in the application of low carbon building due to the following reasons:

I. Oman like most of the MENA including all GCC countries have the same pattern of energy consumptions characterised by reduced energy standards and increased energy uses.
II. Oman ranked in the 10th position in the world and in the 5th position in MENA in terms of the CO_2 emissions per capita as a result of the increasing use of fossil fuels.
III. GCC countries' knowledge about the performance of the regulations and policies is still required in order to encourage higher energy efficiency in buildings, whereas Oman has not yet started to develop an energy policy in the residential sector.

IV. Electricity prices in all GCC countries are very low compared to the existing international prices, constituting one of the major problems behind a reduced adoption of low carbon strategies in these countries.

V. The vernacular architecture is ignored in the current construction industry, which obstructed past benefits for future constructions.

VI. A lack of national drivers for adopting low energy solutions in the GCC still exists, especially in residential buildings, despite current achievements.

VII. Fewer low-carbon residential buildings are constructed compared to the size of the construction industry.

VIII. Available LCB options in Oman need to be investigated because:

  i. There is insufficient literature that discusses the thermal comfort need and the associated energy performances in Oman.

  ii. To implement energy measures in the construction of new dwellings which increased at a high rate and this rate may remain the same for the next few years since the rate of population growth is increasing.

IX. More research is needed to assess social needs and industry support to the available options of low carbon buildings and their acceptance boundaries.

X. The need for benchmarks and guidelines for energy consumption in buildings.

3 Chapter III: Research methodology

3.1 Introduction

The objective of this research is to explore different passive design strategies appropriate to the construction of residential buildings in Oman's hot and humid climate. It sets-out a basis for a framework-guideline describing a low-energy building strategy for this climate. Further, the research provides robust quantifiable data on the strategies for constructing low-energy domestic buildings, which have been adopted in Oman. This chapter examines the generic research concepts and methodologies commonly described in the literature related to built-environment research and the application of this research. A systematic approach is adopted at various stages of this study in order to facilitate the achievement of its aim and objectives. In addition, this chapter addresses the various concepts, which make up the 'world view' of this research then discusses and differentiates between the qualitative and quantitative research methods used. The chapter also explains why a mixed methodology was adopted in this research and the actual techniques used in conducting this study. Finally, it describes how data were collected, analysed and examined in order to support the hypothesis of the research.

3.2 Research philosophy and methods

A common definition used for research study might be as follows: a detailed enquiry or exploration of solutions using approaches aimed at making discoveries that will contribute to the associated body of knowledge (Fellow and Liu, 2008). In addition, research can be described as a structured methodical inquiry that leads to an acceptable scientific solution to a problem or creates new knowledge in the field of the research (Kumar, 2011). Research can be a 'voyage of discovery', whether anything is discovered or not. On the other hand, it is highly likely that some discovery will result because discoveries can be concerned with the process of investigation as well as the topic of investigation. Even if no new knowledge becomes apparent, the investigation may lend further support to existing theory (Dresch, Pacheco Lacerda and Cauchick Miguel, 2015).

There are various methodologies that lead to acceptable results that can be used in any area of research. Nevertheless, for good research results, the chosen methodology needs to be rigorous, systematic, integrated and focused (Peters and Howard, 2001). Further, the methodology is required to fulfil the aim of the research, whether it is pure research or applied research (Holt, 1998). There are several views on research philosophies, which exist within the research community relating to the use of suitable paradigms (Fellows and Liu, 2008). Yin (2009) argued that the choice of an appropriate research method should be influenced by three main factors: the nature of the inquiry, the extent of the researcher's control over the actual behavioural event, and the degree of focus on contemporary events. The common primary classification of research approaches in literature is as follows: quantitative, qualitative, and a combination of the two methods commonly referred to as triangulation (Neuman, 2006).

3.2.1 Quantitative Research

The quantitative research method is used to test objective theories by examining the relationship between variables that can be measured, for example by instruments, so that the data generated can be analysed by mathematical and/or statistical procedures (Creswell, 2009). Fellows and Liu (2008) stated that quantitative research uses the scientific method – in which an initial study of the theory and literature yields precise aims and objectives with hypotheses to be tested. Sarantakos (1998) noted that the quantitative method is objective in nature and capable of providing explanations for social phenomena or processes such as standardisation. Quantitative research can take the form of either experimental or survey-based research (McQueen and Knussen, 2002).

3.2.2 Qualitative Research

Exploring and understanding the meaning individuals or groups attribute to a social or human problem is referred to as qualitative research (Creswell, 2009). Qualitative approaches seek to uncover why things happen in the manner that they do, and to determine the meanings, which people give to events, processes and structures. Qualitative research involves the collection, organisation and interpretation of textual data gathered from talks or observations; these are used in the exploration of the meanings of social phenomena as experienced by the individuals involved in their natural context (Malterud, 2001). One of the features of this research method is the flexibility of the overall research process since the questions and procedures, which emerge (Creswell, 2009), are not usually predetermined. A qualitative research project can be viewed from five different perspectives known as strategies of inquiry (Creswell, 1998), (Denzin & Lincoln, 2000), (Fellows and Liu, 2008) (Table 3.1), (Kakulu *et al.*, 2009).

Research strategies of inquires perspective	**Description**
Biography	The study of an individual and the individual's experiences; for example, what is told to the researcher or collected from archive records.
Phenomenology	The study of phenomena that exist as part of the world in which we live such as events, situations, experiences or concepts.
Grounded Theory	An inquiry aimed at the discovery or generation of a theory.
Ethnography	The studies of people embedded in their natural behaviours and culture.
Case Study	The study of an individual, an event, or a project as a single source or as part of a group of sources of ideas or descriptions of phenomena, project-biographies or illustrative anecdotes.

Table 3.1: Qualitative research: strategies of inquiry

3.2.3 Mixed mode research

This is a multi-method research approach that combines both quantitative and qualitative methodologies in one study (Fellows and Liu, 2008). Sometimes it is referred to as the triangulation method, and it includes methodologies from both the qualitative and quantitative research approaches. In social science, triangulation is described as the mixing of data or methods in order to achieve the aim of the study (Olsen, 2004) (Figure 3.1). One of the reasons why researchers adopt triangulation is to enhance confidence in the ensuing findings; triangulation is thus more appropriate to occasions where researchers seek to verify the validity of their findings by cross-checking them, using another method. Triangulation helps the researcher gain insights and results, and assists in making inferences or drawing conclusions.

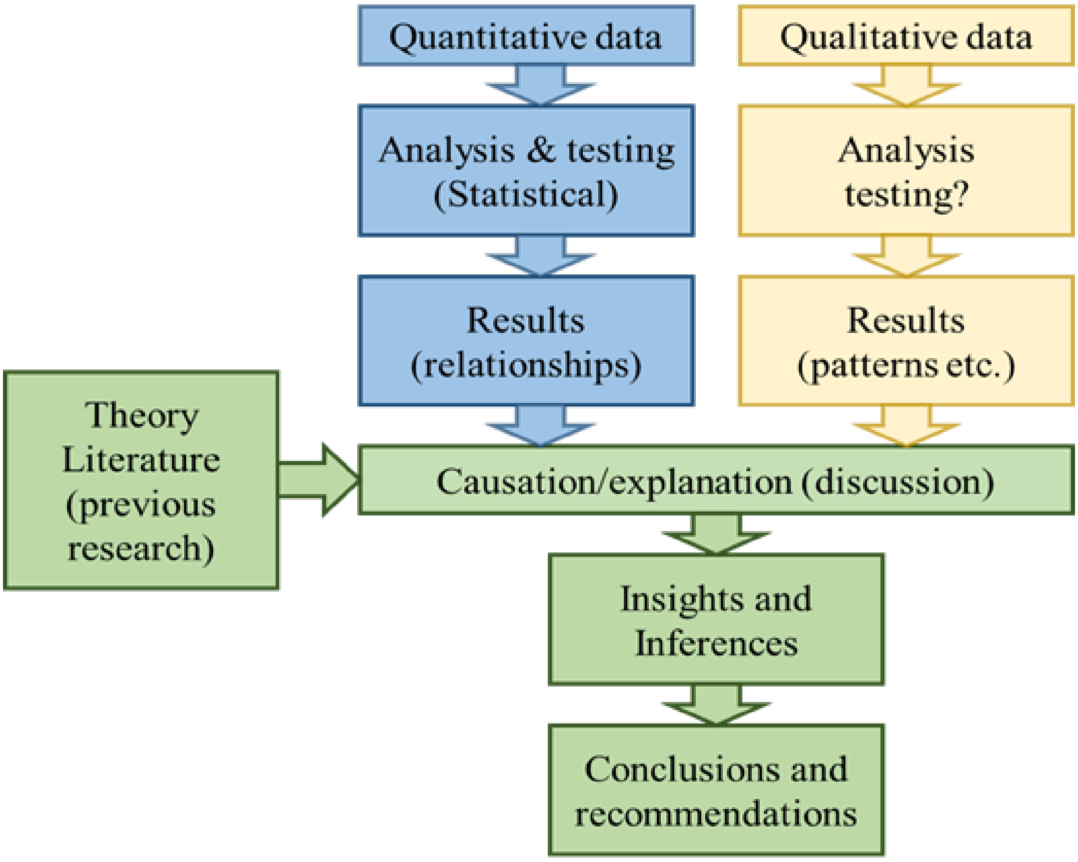


Figure 3.1: Triangulation of quantitative and qualitative data

(Fellows and Liu, 2008).

Triangulation is an approach, which adopts a single method but combines different strategies within that method in one study. Love *et al.* (2002) pointed out two main advantages of combining the qualitative and quantitative research approaches. The first advantage is that it increases the capability to transmit the knowledge in a perceptible form. The other advantage is that findings can provide the researcher with greater confidence in the reliability and validity of the results. Moreover, a mixed methodology has the potential to lead to a better understanding of the investigated phenomena, especially when it not possible to investigate it thoroughly via a single methodological approach. It can also be argued that mixing research methods provides the advantages of each of the methods and eliminates the weaknesses inherent in them. However, there can also be some disadvantages to the use of multi-method research. The researcher needs to be familiar with a great variety of data collection techniques in order to identify which one is most appropriate to a situation. In addition, triangulation could lead to more expense incurred in the collecting of data than a single method would (Venkatesh, Brown and Bala, 2013).

Thus, the mixed methodology approach was adopted in this research in order to maximise the chances of acheiving the research objectives in a more empirical way while benefiting from the strengths of each method (Figure 3.2). In this regard, the research objectives were properly described in order to identify suitable research methods (Table 3.2).

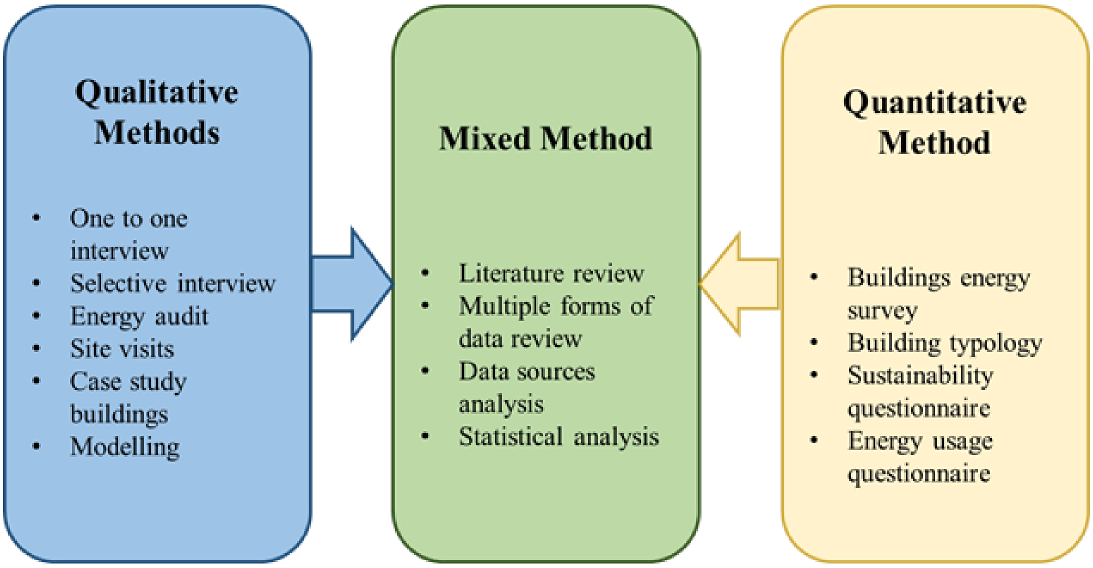


Figure 3.2: Application of methodologies adopted in this research

No.	Objective	Description	Research Method
I	Review the current state of the art as regards sustainable domestic construction in Oman	Study the current codes of practice, construction publications and actual practice	Literature review, surveys/questionnaire and interviews, review of construction practices and materials, review of LCB status
II	Establish suitable research methodology	Investigate the possible research method for the study	Desk Study and literature review
III.	Determine the energy consumption profile and key elements of operational deficiency that increased energy consumption of residential buildings in Oman.	Identify the status of the housing stock typology in Oman, the energy consumption characteristics of buildings and the main building elements affecting the energy use patterns that result in an increased energy use in the residential sector	Review of current building energy consumption from literature, utility bills and buildings users, field based experimental measurements,
IV.	Determine building energy system boundaries, needs and requirements	Illustrate energy flow and end user consumption, identify the main home tasks and their energy consumptions, review building energy efficiency reduction measures	Questionnaire, interview, site visit, energy measurements, Benchmarks energy requirements / m^2, CO_2 emission
V.	Develop design guideline framework for LCB based on EEMs for hot humid climate including:- • Design criteria; • Building elements; • Building materials.	Developing a guideline framework for low energy dwelling and identifies sensitive and robust design parameters that reduce the energy consumed for different purposes in residential buildings by examining energy efficiency measures used in SOTA LCBs	Study of weather profiles, economic measures, desk based study of performance targets in GCC countries who have applied low carbon strategy, Desk based work survey, questionnaire IES modelling
VI	Devise a LCB template to evaluate options of residential LCB in Oman considering:- • Energy requirements • Building operation • Home appliances	Apply the guideline to a number of buildings to validate its efficiency	Desk based study, results collected from energy audit, monitoring, template establishments using Excel book
VII	Map a suitable LCB strategy for Oman using the criteria of the template	Implement LCB energy reduction measures in a conventional building	Desk based study, results collected from energy audit, monitoring, software analysis

Table 3.2: Research methods adopted to achieve the research objectives

3.3 Research concept

This research assumed that implementing a strategy based on adopting energy reduction measures, which have been used in best-practice low-energy buildings, can bridge the gap, which exists in relation to the energy consumptions of residential buildings in Oman (Figure 3.3). In addition, techniques used in vernacular architecture to provide, in traditional buildings, an acceptable level of comfort, but which have been ignored in the current construction industry, can be brought into use again in order to reduce overall building energy consumption.

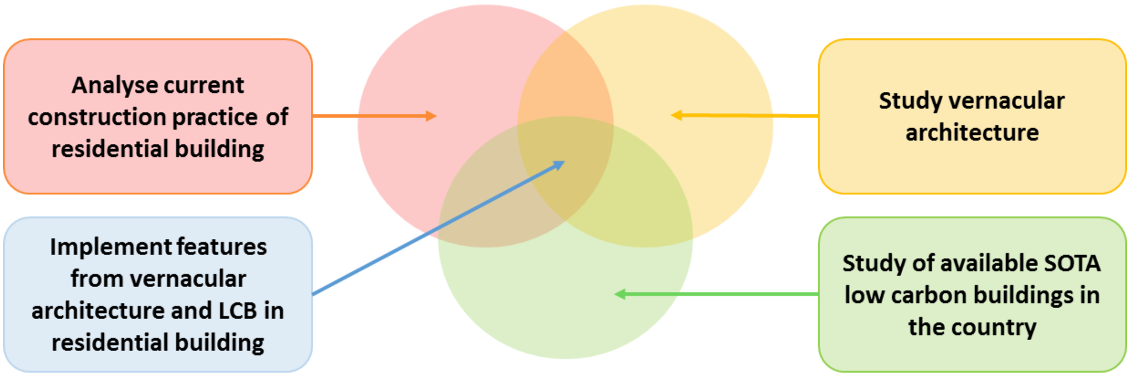


Figure 3.3: The research concept

3.4 Research approach

The research began with an intensive review of the literature concerning the status of low-energy residential building at four levels: international, middle-east, GCC and Oman. This stage highlighted the gaps in knowledge in order to inform the definition of a stable research methodology and tools. Then, the research proper was initiated by discussions with relevant stakeholders (via interviews) to set up the basis for a more detailed inquiry. Further, a survey served as a continuation of the interviews, and also served to validate the results of the interviews and some of the findings from the literature. Thereupon, a case study became imperative for the further exploration of the knowledge gap which had become apparent. Within this case study, physical evaluation/observation, interviews and surveys were used (Figure 3.4).

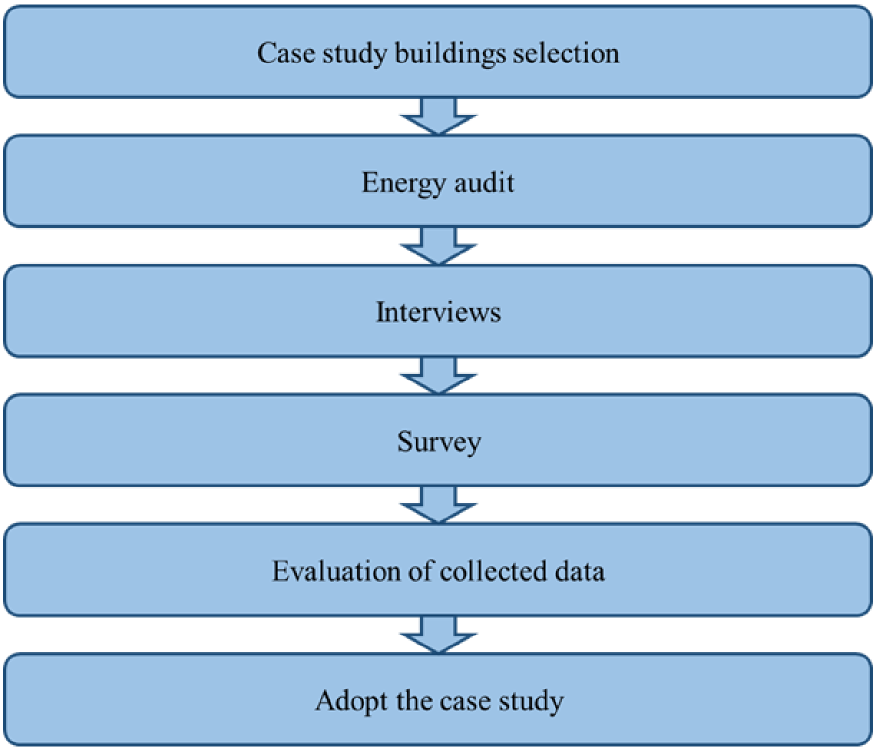


Figure 3.4: Data collection approach

A thematic analysis concept was adopted for the analysis of the data; it is essential to think through the method that will be used for analysis before collecting the data. In this research, this issue was considered thoroughly by listing out the methods of research against each objective as shown in Table 3.2. These objectives became the main themes when analysing the data, which had been gathered through an appropriate method.

3.5 Data collection

Data collection for research work is the process of gathering and measuring information based on targeted variables using an established systematic approach. The objective of data collection is to provide sufficient information to answer relevant questions and evaluate outcomes (Sapsford and Jupp, 1996). Data collection is a major component of research in all fields of study: including the physical and social sciences, the humanities, and business. Methods vary according to research schools; however, the target remains the same – to insure accurate and honest data collection. The selection of appropriate data collection instruments and their correct employment reduces the likelihood of errors occurring. Since the mixed methodology was selected for this research, data collection will involve a literature review, a questionnaire, a survey, interviews and case studies of buildings.

3.5.1 Literature review

A literature review is a review of the available texts of scholarly papers, which encompass the current knowledge, findings, theories, and methods that are relevant to the research topic (Fellows and Liu, 2008). The review of relevant literature essentially served the following three major purposes in this research:

- Clarifying relevant issues of the research topic
- Highlighting the gaps in knowledge and practice
- Providing references to the results

The search for relevant literature was carried out through the study of state-of-the-art (SOTA) low-energy buildings, relevant standards and codes, and the latest publications from reports and media. A literature review was conducted both at the outset and was carried on all through the research process on relevant topics within the research domain such as:

- An overview of sustainability in the construction of low-energy building.
- The historical background of the vernacular architecture of Oman and GCC countries.
- Available legal frameworks and regulations.
- Residential building physics and materials.
- Energy consumption characteristics of a residential buildings.
- Barriers to the widespread construction of low-energy buildings in Oman and GCC countries.
- Built environment impacts on climate.
- Global concerns for a low carbon environment and the efforts made towards the zero carbon buildings target.
- Low carbon and renewable energy technologies and their opportunities, operation and challenges in Oman.

3.5.2 Interviews

This was the method, which was used to gather qualitative data in order to collect in-depth and up to date information about Omani residential buildings standards, building regulations, energy consumption, energy demand, governmental plans to overcome the energy challenges in the future, methods to save energy and other relevant technical data. The interviews were undertaken with specialists, experts, architects and engineers during field trips to Oman (01/06/2014–5/10/2016).

The interviews were with qualified government personnel, representatives of organisations and universities, and company representatives who were in an appropriate professional position and had a good knowledge of the research topic (Table 3.3). The interviews were of a semi-structured type; thus, specific questions were prepared for each interview depending on the visit's purposes and the interviewee's background. The main aim of the interviews was to cover the research questions, bridge missing data, and collect up to date data in order to set boundaries for the research.

Interview	Concern participant	Objective of interview
Interview 1	Governmental authorities, research council	To provide incentive support
Interview 2	Designers of reference low carbon building	To discover the barriers and difficulties involved
Interview 3	Electricity Authorities representative	To discover any progress which has been made in the legislation and legal framework
Interview 4	Contractors	To find out what the market's ability to support low carbon building strategies is.
Interview 5	Solar energy companies	To discover the progress which has been made, and the obstacles which have been encountered in the adoption of RE

Table 3.3: List of Interviews.

3.5.3 Survey and Questionnaire

Surveys were used to collect primary data about the characteristic energy consumption patterns and the social interactions of occupants living in a residential building in Oman. Then, a set of questionnaires were designed to collect data on the local communities and the status of low-energy buildings. The choice of answers for each question was from a set of pre-determined responses. This was so that these results would be fully focused on the core of the results obtained from the initial survey (Table 3.4).

Description	Participant Concerned	Objective of questionnaire
Survey 1	Engineers from the municipality and the ministry of housing	To identify gaps in knowledge
Survey 2	Data from occupants on residential buildings' characteristics and electricity consumption	To identify cases of energy deficit
Questionnaire 1	Public	To gauge awareness of the impact of residential building energy consumption

Table 3.4: List of surveys and questionnaires

3.5.4 The selection of case study as a method

This method was selected because it was felt that it would assist in the understanding of the way recent residential buildings in the Sultanate of Oman are working in terms of building typology, building fabrics and end-user energy consumption. This part of the research will focus on different case studies, examples, and an examination of typical residential building materials and energy consumption related to buildings in Muscat, the capital city. The case study buildings used for this thesis can be categorised into two typologies of residential buildings, that is, low carbon buildings and conventional buildings representing typical Omani dwellings. The reviewed LCBs were five green buildings constructed for The Research Council (TRC), Muscat as part of a national competition in designing and constructing green buildings in Oman. Communication with TRC was undertaken before the selection of these buildings as reference LCBs in order to obtain permissions and access to these buildings.

3.5.5 Reference case study buildings

From the results of the literature review and the site visits, three reference conventional buildings and three state-of-the-art low-energy buildings were selected for an in-depth energy analysis. The selection of buildings for detailed study was based on several factors (Table 3.5). The secondary data includes 100 typical residential buildings and 5 low carbon buildings, which were reviewed in terms of energy consumption behaviours (Table 3.6). However, to make an in-depth study, considering the justifications given in Table 3.5, and the limitations in terms of time and funds for this research, it became necessary to select three buildings for intensive analysis, although some lessons learnt in the general cases helped in the drawing of conclusions.

Factor/constrain	Justifications
Suitability	The selected study buildings are of a similar size and can house a similar number of occupants: all the buildings were constructed from similar construction materials, all the conventional buildings are in Muscat, all the buildings are of a similar age.
Primary data availability	The reference buildings were selected on the basis of the availability of plans, their energy consumption, home ambiance data and occupancy pattern
Relevance	Two of the five LCBs were not included in the analysis: Dhofari Eco-House (LCB1) and SQU House (LCB4). LCB1 located in Salalah at distance of 1200 km from Muscat where the weather conditions are quite different from those in Muscat, LCB4 had not been completed by the time measurements were to be taken.
Accessibility	The selection of reference buildings, especially the conventional buildings, was made on the basis of the accessibility of these buildings whenever required.
Validity	The validation of the drawings in relation to the existing buildings, and the validation of the energy usage reported with the energy consumptions recorded by the utility companies.

Table 3.5: Factors and constraints of selecting reference buildings

Conventional buildings		
Building	**Description**	**Photo**
CB1	A two-story 4 bedroom house (212 m^2), located in Muscat	
CB2	A two-story house (320 m^2) located in Al khuwair, Muscat	
CB3	A two-story house (240 m^2) located in Al khuwair, Muscat	
CB4	A two-story house (340 m^2) located in Al Amirat, Muscat	
CB5	A two-story house (310 m^2) located in Qurayat, Muscat	

Low carbon buildings		
Building	**Description**	**Photo**
Dhofari Eco-House (LCB1)	A two-story (324 m^2) house in Salalh, designed by Dofar University.	
GUTech Eco house (LCB2)	A two-story (257 m^2) house in Seeb, Muscat designed by German University of Technology, Oman.	
HCT GreenNest (LCB3)	A two-story (287 m^2) house in Al-Kuwair, Muscat, designed by the Higher College of Technology.	
SQU House (LCB4)	A two-story (354 m^2) house in Al-Khod, Muacat, designed by Sultan Qaboos University.	
BUSTAN OMAN (LCB5)	A two-story (346 m^2) house in Nizwa, Designed by Nizwa University.	

Table 3.6: Selected reference buildings

3.5.6 Energy audit

The definition of a building energy audit according to the Standard EN 16247-1:20122 is: *‘‘a systematic procedure to obtain an adequate knowledge of the profiles of energy consumption of an existing building or group of buildings, an industrial and service private or public, in order to identify and quantify in terms of cost effectiveness of energy saving opportunities and the relationship of what is revealed’’*. Building energy assessments often require energy audits in order to determine energy efficiency and deficiencies. The energy audit, carried out by an auditor, provides an overall assessment of the building, and can lead to the determining of the causes of inefficiency. Energy audits were conducted in this research to obtain the characteristics of buildings and energy system elements (Ingle *et al.*, 2014).

3.5.7 Energy monitoring

The main objective of an energy monitoring study is to estimate the actual comfort achieved by the building vs its energy performance efficiency – in a real time environment. This means that the conditions in the internal spaces must be measured in terms of thermal comfort and energy consumption; this information will be put alongside the energy consumed for daily home activities, which includes that used for hot water requirements, lighting and home appliances. To achieve this task, the external microclimate, the average internal environmental conditions, and the energy consumed are recorded for analysis. The physical environmental variables that need to be assessed when conducting a thermal comfort survey are outlined by Nicol *et al*. (2012). For the purposes of evaluating the energy used by a building the following variables are monitored:

- Outside air temperature, relative humidity, wind speed and direction, and solar radiation on the horizontal plane.
- Internal room variables: internal air temperature and relative humidity.
- Main household energy consumption activities are monitored and recorded to evaluate the overall energy performance of the building – as compared to the energy consumption of conventional buildings.

3.5.8 Monitoring devices and strategy

An online monitoring method was used as it gave direct measurements, which could be accessed remotely. The monitoring system and devices were setup in the LCBs with help from The Research Centre (TRC), Muscat. TRC was aiming to monitor the five LCBs as part of a local green buildings competition between Omani higher education institutions. Hence, cooperation was established with TRC such that the data collected from their monitoring devices could be used in this research (AlShamsi, 2014). The number of data collecting sensors necessary was determined according to the judgement of the person conducting the monitoring; this varied in response to room size, layout and the purpose of the measurement (Nicol *et al*., 2012). Room temperature may vary from place to place. Therefore, in thermal comfort surveys, it is recommended that measurements are taken at a vertical height of 0.6m above the floor for a seated person or at the working surface level and not less than half a metre from any wall (Nicol *et al*., 2012). In relation to the overall performance of a space, the measurements can be taken from the centre of the room providing that the sensors are away from any objects, which could disturb them. For accurate measurements, it is better to use more than one sensor at the same location and record an average reading. Since the internal spaces of LCBs are small, for the purposes of this study one sensor was used per space – located in the centre of the space at 1.2 m above the floor, at least 0.5m from the wall, and away from any objects, which might disturb them.

In this research, the main objective of monitoring was to determine the comfort level in relation to energy consumption; for this, it was recommended to take measurements for a full year. However, restrictions regarding building access usually determines the dates on which monitoring can be conducted. Hence, monitoring could be undertaken for one month only.

The monitoring system was used to measure and record three main aspects: the internal spaces' comfort conditions, the electricity consumption, and the outside weather conditions (Figure 3.5) and (Figure 3.6). The monitoring equipment consisted of a data acquisition system connected to sensors measuring the internal zone temperatures and humidity, and the electricity consumption of home appliances. In addition, the system was connected to a weather station located at an elevated position on top of the roof to measure the outside temperature, humidity, solar radiation and wind speed. The figure below illustrates the architecture of this system.

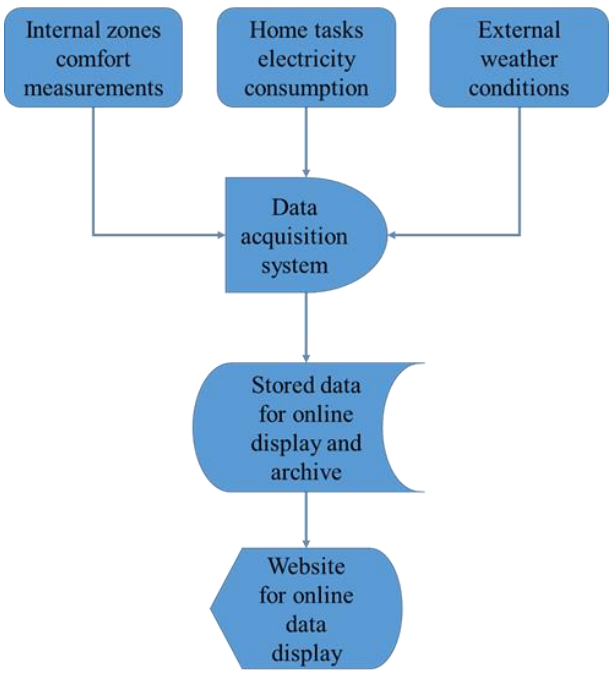


Figure 3.5: Monitoring system principle

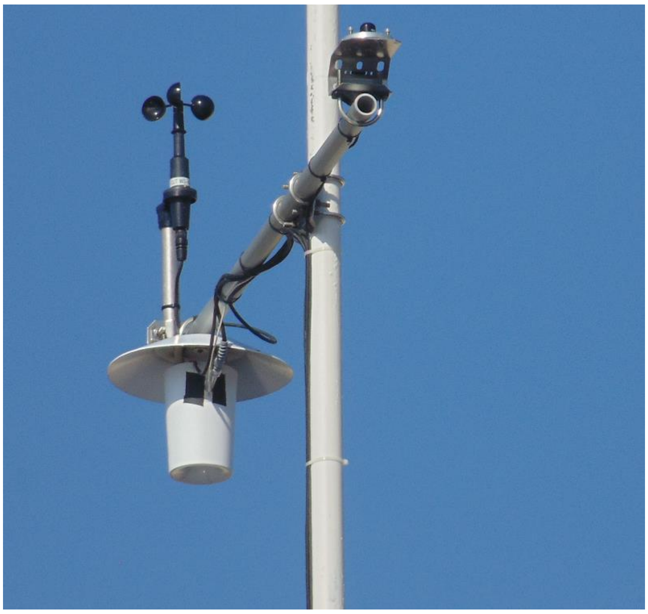


Figure 3.6: Weather station in LCB3 (Appendix E)

The zone temperatures and humidity's were measured by one combined unit placed on a tripod 1.2 m high and located away from any direct air flow from air-conditioning or windows or any hindrance that may have affected the recorded data (Figure 3.7).

Figure 3.7: Zone temperature and humidity measuring device

The temperature and humidity measurements alongside the energy consumption data obtained from electricity main switch board (Figure 3.8) were sent to the data acquisition system, which saved it and then sent it to the web page. The recorded data was updated automatically every 20 seconds and presented in the form of an instant direct reading and also in a cumulative graphical form spanning the past 30 hours. Similarly, outside temperature, humidity, wind speed and solar radiation were collected from a weather station located on the roof and presented to the website in the same manner.

The data acquisition system also recorded the electricity consumption of the major household appliances, which were classified into six major categories: lighting, home electronics, HVAC, refrigerator and freezer, hot water and washing machines.

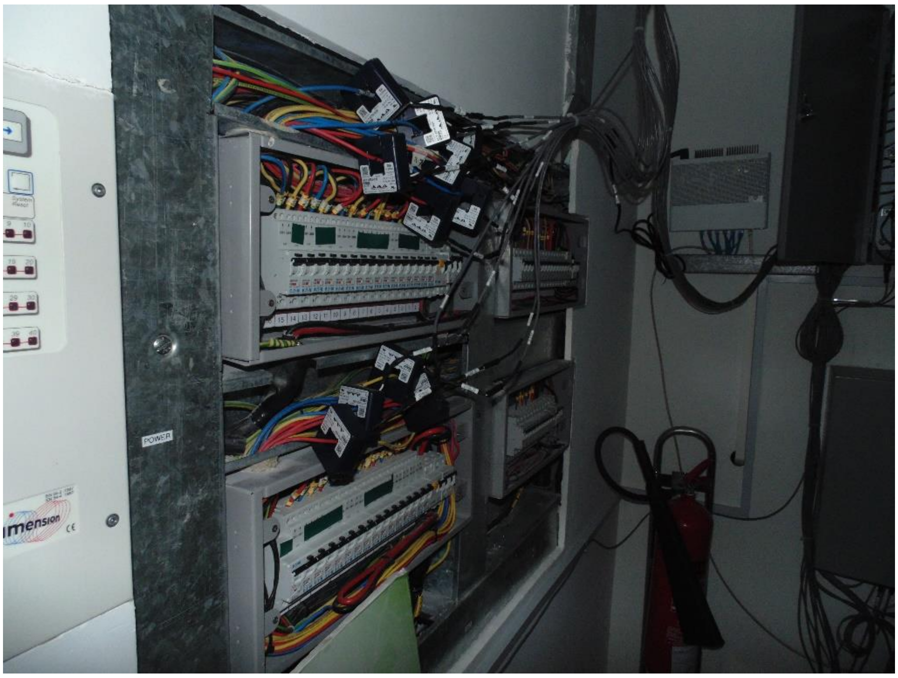


Figure 3.8: Electricity consumption data collection

3.5.9 Simulation of Energy Consumption

The next stage of the research required the use of computer simulation software in order to evaluate the energy efficiency measures (EEMs) implemented in the exemplar LCBs. This was carried out via energy simulation models. This step was intended to support the aims of the research by providing a clear validation and estimation of the energy efficiency of the residential buildings. The simulation required investigations into building fabrics, the geometric dimensions of the buildings and also the energy consumption of the buildings. The IES Virtual Environment (VE) was selected for the simulation phase of this research. It is a suite of building performance analysis applications used to test different building options, identify passive solutions, compare low-carbon and renewable technologies, and draw conclusions on energy use, CO_2 emissions and occupant comfort (VE for Architects | Architectural analysis package, 2017).

Energy simulation was used for this thesis for two main purposes. The first purpose was to establish a base case modelled energy consumption of the reference buildings. The second purpose was to evaluate the different design strategies.

3.6 Data collection considerations

Regardless of the field of study or the research methodology in use, accurate data collection is essential to maintaining the integrity of any research. In addition, the general and specific considerations that have been taken into account in this context must be clarified. There are several ethical issues that must be considered when collecting any type of data. Thus, care was taken to minimise the shortcomings identified for each of the research approaches. The actions taken in this regard are as follows:

- The samples for the interviews were relatively small because of the in-depth requirements of the investigations; hence, interviews were conducted with very experienced professionals involved in the construction industry currently and in respect of residential buildings in Oman.
- The data collected and analysed from the interviews were the results obtained from a structured set of questions. These were open ended in order to allow adequate freedom for participants to express their opinions based on their experience.
- Interviews were recorded via a digital voice recorder for future reference. The verbatim transcriptions were sent back to the interviewees for editing and correction.
- Before each questionnaire, a pilot study was conducted and the questionnaire was reviewed in relation to this before the main survey was administered.

- Attention was paid to the selection of the buildings to be surveyed, in order to obtain similar sized buildings with similar levels of occupancy.
- The reference LCBs had been constructed for a green building design competition, specifically for the climate of Oman. This had received generous funds and donations from governmental bodies and many companies. Therefore, the real construction costs were evaluated by local contractors.
- A variety of precautions were taken in the delivery of the questionnaires, such as hand delivery and physical visits to retrieve them in order to maximise the responses, data protection and consent, which are important ethical considerations.

3.7 Buildings energy calculations principle

The methods typically used to predict and calculate building energy consumption are based on deterministic models that accounts for buildings' energy demand according to pre-defined input data describing the building's sub-systems, usage patterns and weather conditions. However, the complexity of real-life buildings is influencing their whole-system energy calculations. The main cases of building energy complexity is due to factors including building conditions, age, appliances type and efficiency, appliance age, occupants' financial status and social life inside buildings. This reduces the accuracy of deterministic approaches, which their capabilities are unable to deal with unknown or uncertain input parameters. Hence, the model validation and calibration against measured data will accounts for these additional socio-economic factors which are responsible for this inaccuracy, which cannot be predicted due to real-life building energy complexity.

For any energy calculation and demand, it would be necessary to specify the boundaries of energy flows with in the building. Usually, all energy used in the buildings is recommended to be considered in the calculation. Energy calculation determines energy use in relation to indoor climate control, the heating of hot water and the operation of electrical equipment. These calculation are performed using deferent methods explained by standards, building certifications and rating schemes. An example of these methods is ISO/TC 163 "Thermal performance and energy use in the built environment". This standard involves test and calculation methods for energy use in buildings, including the industrial built environment; test and calculation methods for heating and cooling loads in buildings; test and calculation methods for daylighting and ventilation / air infiltration. Also degree-days method is another method used to calculate required energy for thermal comfort in buildings. It is a tool that can be used in the assessment and analysis of weather related energy consumption in buildings. This method is selected for energy consumption calculation for thermal comfort in this research because of its simplicity and applicable in any region in the world.

The methodology for assessment of building energy in this research will involves estimating the building energy consumption and demand based on building geometry, materials, home appliances and usage. The energy demand estimation is required for this research in order to evaluate building energy consumption and requirements under deferent scenarios.

The scope of calculation based on engineering techniques range from simple calculation of usage to complex concepts such as heat and mass transfer. The analysis of the building energy consumption includes the possible renewable energy generated within the building site, where the combination of energy consumption together with the generated in site renewable energy will be referred to as the residential building energy system. The principles of estimating the energy consumption of building is by grouping of energy end consumers in the building. The energy consumers groups in building are based on six home tasks:-

- Thermal comfort (HVAC);
- Lighting (L);
- Hot water requirements (HW);
- Washing (W);
- Refrigeration (R);
- Electronics devices (ED).

The building energy consumption predicting tool which will be created for this research will be based on a static approach assuming a steady-state condition of the building. In this tool the energy estimation of buildings includes both energy consumptions and demands based due to the architectural configuration of the building as well as consumption related to the people in the building. Based on this the energy consumption prediction tool will be made based on the following:-

- Home appliances sizes and frequent of use
- Occupant behaviours and usage patterns
- Building energy system efficiency and ratings.

While the energy demand calculation considers the following factors:

- Building architecture including size, geometry and orientations
- Environmental interaction: heat transfer (both losses and gains) between building and environment;
- Home appliances conditions including usage profile;
- Energy requirements directly related to the presence of people in the building, considers hot water supply, electric and electronics devices.

3.8 Chapter summary

A general overview of research concepts and methodologies has been presented in this chapter. It identified that research may mean different things to different people. Research is a form of logical or systematic, detailed and careful inquiry, aimed at making discoveries that will add to knowledge; it is also solution-seeking in a methodical manner, that is, research is either looking to develop or enhance a theory (pure research) or to solve a problem (applied research).

This chapter has reviewed the two key research approaches (quantitative and qualitative), and also the mixed method referred to as triangulation – which was found to be most suited for this research because of its exploratory nature. The methods adopted to investigate each objective of this research have also been described, along with the general precautions taken and how the resultant data was analysed; adopting the thematic content analysis approach for the qualitative interviews, and the BUS methodology as a POE approach for the case study buildings. The ethical precautions taken, as proposed by the faculty Ethics Committee, were also enumerated in this chapter.

The methodology of this research was adopted on the assumption that designing strategies for a low carbon residential building in the hot and humid climate of the Sultanate of Oman is capable of bridging the gap which exists in the energy consumption of residential buildings. Hence, this research analysed how adopting cost efficient energy measures have been implemented in state-of-the-art low carbon buildings in the country.

4 Chapter III: Main elements of operational deficiency

4.1 Introduction

In Oman, the application of low-energy buildings is subject to operational deficiencies because market and building owners are more interested in the cost of the building rather than in the environmental impact of its operation (Saleh and Alalouch, 2015). Therefore, occupant behaviours are instrumental in terms of increasing the usage of energy (Al-Badi, Malik and Gastli, 2011). These facts, and the absence of a regulatory framework on energy performance of the building, have led to deficiencies in the efficient use of energy in buildings (Saleh and Alalouch, 2015). This chapter identifies the main elements of operational deficiency that are hampering the construction of future low-carbon buildings in Oman. The status of the housing stock typology in Oman, the energy consumption characteristics of buildings and the main building elements affecting the energy use patterns that result in an increased energy use in the residential sector, are reviewed. In addition, barriers and limitations to the wide spread adoption of low carbon buildings in Oman are reviewed in order to identify potential viable solutions. Thereafter, a roadmap of low-carbon strategies is proposed to help the country overcome the adverse effects of energy usage in buildings due to a poor regulatory framework.

4.2 Introduction to Omani housing stock

Oman faces a significant housing shortage due to its dynamic demographics, with a growing younger population (Figure 4.1). This exerts pressure on the residential market to provide the required housing units with an increased rate of urbanisation resulting in the construction industry focussing on the quantity of the buildings rather than on their construction quality (Majid, Shuichi and Takagi, 2012). According to National Centre for Static and Information, the increase of required housing units in Oman is estimated at a rate of 10% per annum. Additionally, household sizes have increased in the past few decades (Majid, Shuichi and Takagi, 2012), (Soheir Mohamed Hegazy, 2015) with an associated increase in the use of domestic electrical equipment (Jones, Fuertes and Lomas, 2015). These facts have resulted in increased electricity demands in the housing sector from 9% to 59% of total energy consumed in the period from 1970 to 1999 ((Energy and Resources- Oman, 2014).

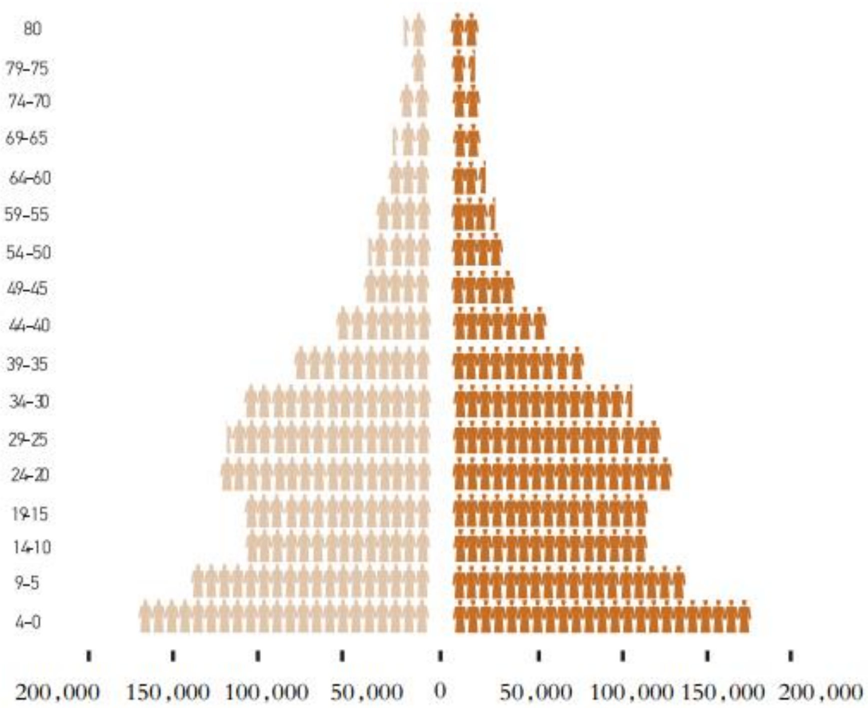


Figure 4.1: Demographics of Oman

(Source: Population Statics, 2016)

In 2012, the building sector accounts for 55% of the electricity usage and its associated greenhouse gases (GHG) (Al-Badi, Malik and Gastli, 2011). This is set to continue increasing due to the increase of urbanisation and substantial development of new housing (Figure 4.2). The utilities companies are expecting increases of electricity demand for residential sector of 8.5% (Al-Badi, Malik and Gastli, 2011). Therefore, it is essential to reduce the energy consumption in buildings in order to address the national energy and environmental challenges and to reduce costs for building owners and tenants. Oman Power & Water Procurement Co. (OPWP) expected an increase in electricity demand of 9% per year from 2016 to 2021 (Projections of the future power and water system in Oman, 2017), whilst oil and natural gas, the primary energy source for generating electricity, is a depleting energy source.

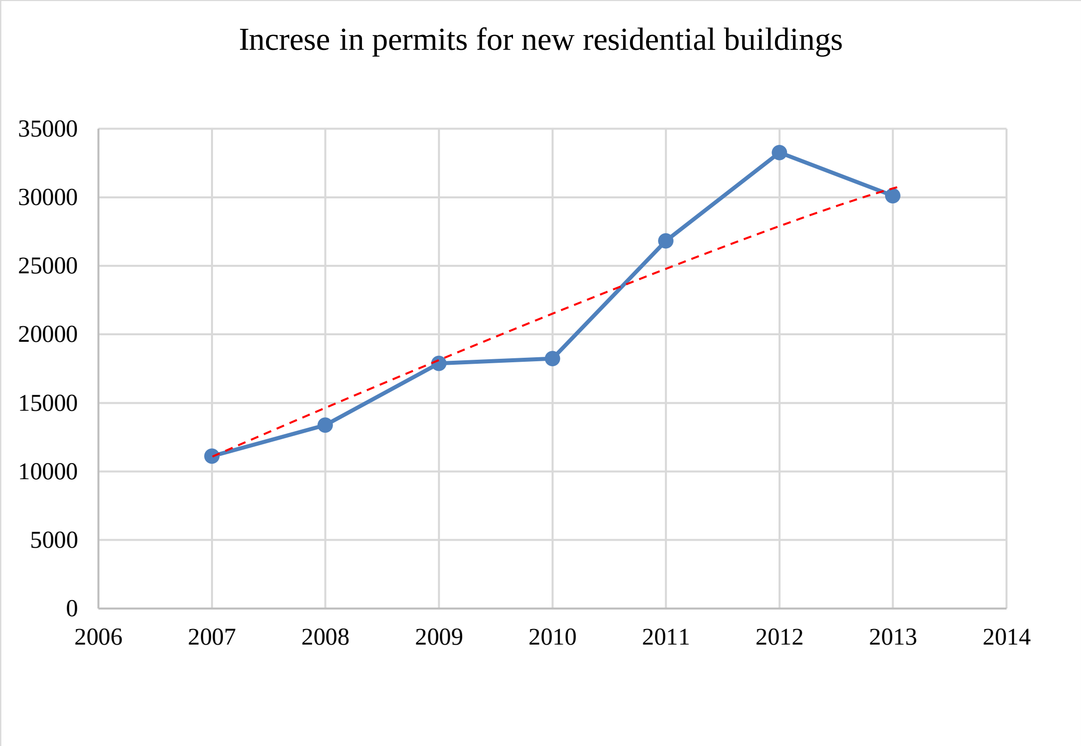


Figure 4.2: Increase in construction of new residential buildings in Oman

(Source: Monthly Statistical Bulletin, 2016)

4.2.1 Review of existing housing typologies

Existing typologies of residential buildings can be used in order to understand the energy performance of the building stock by building typology (Ballarini *et al.*, 2017). At present, typological data and criteria are widely used at the international level in order to inform the implementation of energy policies (Corrado and Ballarini, 2016). Representative reference residential building typologies are also used for modelling the energy performance of the building portfolios in order to support regional or national energy saving plans. Building typology classifications are normally constructed based on building purpose, size, construction materials, region, age and design (List of buildings and structures, 2017), (Theodoridou, Papadopoulos and Hegger, 2011). In Oman, there are no such classification criteria for the residential building sector. According to the real estate sector in Muscat, the available residential properties are classified as traditional Arabic houses, residential annexes, flats, apartments, twin houses and villas (Figure 4.3). This classification is very limited and does not benefit this research as it does not include the construction materials used or the age of the building, required for the evaluation of the building's energy performance. Therefore, a classification based on a combination of the available residential housing criteria in the local market with respect to the local regional construction practice mentioned in 2.6.1, (Muscat Real Estate, 2017), (Architectural styles in Oman - the genius of construction and efficient performance, 2017) and established classification criteria will be combined for this research (Table 4.1). The established classification is based on four main parameters, namely building age, size, style and construction materials. Since the economic factors were decisive in terms of changing the construction patterns in the area, the age of the buildings will thus be based on the main economic changes in the modern history of the country.

Building class	**Construction period**	**Construction materials**	**Description**
Traditional Omani house	Before the 1970s	Clay, stone and tree palms	Wide external walls and small windows
Arabic house	From the 1970s to the 1990s	Stones concrete blocks and wood	Thin walls, narrow windows and rooms around the courtyard
Residential annex	From the 1990s up to this date	Concrete block walls and reinforced concrete slaps	Thin walls, wide windows, normal size of dwelling not exceeding 100 m^2
Flat	From the 1990s up to this date	Concrete block walls and reinforced concrete slaps	Residential unit in a complex or multi-unit building
Apartment	From the 1990s up to this date	Concrete block walls and reinforced concrete slaps	Part of the building, which constitutes an independent residential unit may be attached to another residence from both sides.
Twin house	From the 1990s up to this date	Concrete block walls and reinforced concrete slaps	House attached to another house from one side only
Villa	From the 1990s up to this date	Concrete block walls and reinforced concrete slaps	An independent residential unit consisting of one or more floors connected by an indoor staircase.

Table 4.1: Classification of the residential building typologies

Based on the year of construction, three categories may be identified:

a) Buildings constructed before 1970, (Architectural styles in Oman - the genius of construction and efficient performance, 2017)
b) Buildings constructed after 1970 but before the creation of the first construction regulations in 1992 (Local Order No. 23/92 Building Regulation For Muscat, 1992) and,
c) Buildings constructed after the establishment of the construction regulations in 1992 (Raupach *et al.*, 2007).

Fig 3.3 (a): Arabic house Mud-bricks house

Fig. 3.3 (b): Mud-bricks house

Fig. 3.3 c: Villa

Fig.3.3 d: Flats building

Figure 4.3: Sample residential building typologies in Oman from the 1970s until today

Buildings constructed before 1970 (pre-oil era), were considered to be the oldest existing buildings, normally made from local materials and did not use modern cement (An Architectural Tour through Oman, 2017). The construction of this type of buildings ceased after the 1970s, as they did not constitute a requirement among local people and so were no longer adopted by the construction industry (Majid, Shuichi and Takagi, 2012). Such buildings were referred to as “mud-bricks houses” or “traditional Omani buildings” (Majid, Shuichi and Takagi, 2012), (Al-Hinai, Batty and Probert, 1993).

The second typology of residential building based on age was represented by houses built between the 1970s and the 1980s at the beginning of the oil industry revolution, and before the establishment of the construction regulation (Architectural styles in Oman - the genius of construction and efficient performance, 2017). This type of building was mainly constructed from concrete blocks made from cement products and roofed by wood and/or concrete. The Omanis normally referred to them as “Arabic houses” (Muscat Real Estate, 2017).

The third category of residential buildings based on age comprises buildings constructed after 1992. These were built from concrete and were more popular in the public and construction industry. These buildings were further sub-divided into residential annexes, flats, apartments, twin houses and villas. Individual villas were the most popular among residents, as they provided them with privacy as required by Arab and Islamic traditions (Monthly Statistical Bulletin, 2016). This can be seen from the increasing of number of Omani families living in villas compared to those living in flats and apartments (Monthly Statistical Bulletin, 2016). The annual increase in the number of occupied housing units is estimated at 10% whilst the annual increase of the number of occupied villa’s is estimated at 21%. A survey conducted by the national centre for statics and information surveyed 3520 Omanis about the preferred housing typology for Omani families, revealed that 71% prefer villa (Figure 4.4) (Monthly Statistical Bulletin, 2016). From Therefore, villa typology of housing was selected within the framework of this research.

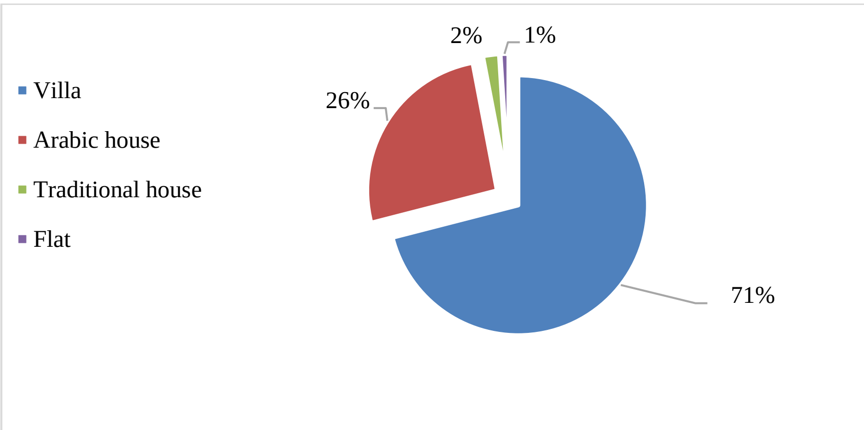


Figure 4.4: Percentage of preferred housing typology for Omani families

(Source: Monthly Statistical Bulletin, 2016)

Villa designs may differ from one to another, but room layout and the zoning of the building are generally the same. Most single-family houses in Oman have two floors, where the ground floor usually consists of semi-public setting and dining rooms with semiprivate spaces kitchen and living. Semi-public spaces are provided to receive guests, whereas semi-private areas can receive family members and female guests (Guidelines for Sizing Shading Devices for Typical Residential Houses in Muscat, Oman, 2017). The second floor consists of semi-private (Family Living) and private spaces (Bedrooms), where only family members are allowed (Figure 4.5).

Figure 4.5: Sample of 4-bedroom Omani house layout

(Source: Muscat Municipality, 2017)

This typology of residential building adopts few low-carbon building techniques because a typical Oman dwelling has un-insulated construction elements, energy efficient windows or efficient ventilation Passive solar building design techniques or active solar technologies are not implemented within the current residential building construction framework. Despite the abundance of solar energy, these homes lack the use of solar hot water or of solar energy. Additionally, residential buildings do not benefit from energy saving devices, such as efficient lighting and smart energy appliances. Hence, current conventional residential building shows lack of application of low carbon techniques (Table 4.2).

Low carbon criteria	Best Practice LCB	SOTA	Conventional buildings
Design	Zoning of spaces within building, application of passive design	Zoning, building shape reduces heat gain, application of passive house design	Design and zoning not considered
Envelope	High U value materials, thick external walls	High U value materials, thick external walls, multi-layers	Single layer, thin external walls
materials	High diurnal thermal material	Modern high-tech. multi-layer material	Concrete products
Insulations	Use of insulation in external walls	More than one layer of insulation integrated within external walls	Insulation not in use
fenestration	Size reduced, double glazing, avoided in the South façade	Size reduced, double glazing or multi-pane, argon filled windows or Vacuum Insulated glazing, avoided in the South façade,	Single layer windows not avoided from heat gain
orientation	Long oriented axis east – west	Long oriented axis east – west	Long axis orientation not considered
Shading	Use of shading devices	Use of shading devices, shadings on the roof	Not in use
Solar hot water	Uses of solar hot water,	Uses of solar hot water,	Not in use
Renewable	Use of PV panels	PV panels integrated in the design to produce extra shading on the building	Renewable energy source not used
Equipment	High efficiency equipment	High efficiency equipment	Un rated equipment
energy saving practice	Use of energy management, smart home appliances	Use of energy management, smart home appliances	No indicator on energy saving practice

Table 4.2: Deficiency in low carbon techniques in conventional building

4.2.2 Residential building materials and construction methods

Concrete is the main construction material used for all newly constructed buildings in Oman as it is flexible and widely available (Majid, Shuichi and Takagi, 2012). Furthermore, the 1992 construction regulations in Oman concentrated only on the frame structure of buildings and did not include the load bearing wall structure. This option supports the use of concrete more than other materials. Concrete is a construction material used globally, but its thermal properties require more consideration when used in hot environments, such as the climate of Oman. In the case of concrete buildings, it is recommended to reduce the heat gain in a hot climate by applying LCB techniques such as shading, insulation, or double glazing combined with thermal mass in order to stabilise diurnal temperature variations during the day (Majid, Shuichi and Takagi, 2012).

The report prepared by the UCL Energy Institute (2014) on residential energy consumption in Oman revealed that the size, shape and orientation of a building as well as the thermal properties of the building fabric all contribute to its overall energy consumption. The report stated that all the surveyed homes were constructed either from concrete blocks or cast concrete walls with the roof and floors constructed from reinforced concrete. Building envelopes were made of single layer of concrete blocks, whereby the internal and external walls had the same thickness and were made from the same materials despite the need for thermal insulation in the external walls. In addition, buildings were not provided with shading devices on windows as required. The thermal performance of the installed glazing was also poor, with 70% of homes being single glazed. Only approximately 10% of homes had some form of reflective coating on the glazing to reduce the transmission of unwanted incident solar radiation. External shading devices, such as shutters, were found in approximately 10% of homes and just over half were exposed to shading from neighbouring buildings or trees. Home appliances were not rated for energy efficiency and the lighting was not energy-saving fitments or luminaires (Sweetnam, 2017).

4.3 Energy conservation practice in residential buildings in Oman

Energy consumption in homes in Oman is linked to six main domestic sources including HVAC (Heating Ventilation and Air Conditioning), lighting, refrigerators, domestic hot water, washing machines and home electronics (Sweetnam, 2017). The energy required for these sources is directly or indirectly affected by physical and social factors (Table 4.3).

Sources of domestic energy use	**Physical factors that affect the energy use/load.**	**Social / cultural factors that influence the final energy use.**
HVAC	Building envelope, orientation, shading and air-conditioning device energy rating	Number of occupants, health, age, attitude, energy management
Lighting	Use of natural lighting type of lighting devices	Occupant attitudes
Refrigeration	Size of refrigerators, age, type	Life style, frequency of opening, amount of stored goods
Domestic Hot Water	Use of solar heater, number of occupants, type and size of water heater	Occupant attitudes
Washing Machine	Number of occupants, size of machine and energy performance	Occupant attitudes
Home Electronics	Number of occupants, size of electronics devices and energy performance	Occupant attitude, standard of living

Table 4.3: Energy consumption tasks and drivers

The household information on energy consumption, conservation opportunities and the energy performance of technologies is expected to affect the adoption of the energy conservation practice (Cao, Mathews and Wang, 2015), (Lynham et al., 2016). In addition, the patterns of current energy consumption depend on the level of metering and feedback, the level of technology used for home devices, and the households' willingness and ability to manage the conservation of energy. Households need to be aware of and be able to evaluate energy efficiency opportunities (Schipper & Hawk, 1991). For example, Scott (1997) observes that household knowledge about potential energy savings is associated with an increased implementation of energy efficient technologies (Al-Badi, Malik and Gastli, 2011).

The UCL Energy Institute (2014) reported that energy consumption at the scale of individual typology and the residential stock of Muscat indicated that the annual energy consumption of individual villa’s was higher than for all the other classes of residential dwellings (Figure 4.6). This is due to the size of the villa being larger than in the case of the other typology. Alalouch & Saleh (2015) suggested that an energy efficient house should not consume more than 120 kWh/m^2/year, whereas the analysis of energy requirements for Omani villa’s conducted by the University of Nizwa, Oman showed the annual requirement for an eco-house in Oman is 109.6

kWh/m^2/year (BUSTAN OMAN, 2015). Hence, this research will consider energy efficient residential building energy requirement of energy in this range.

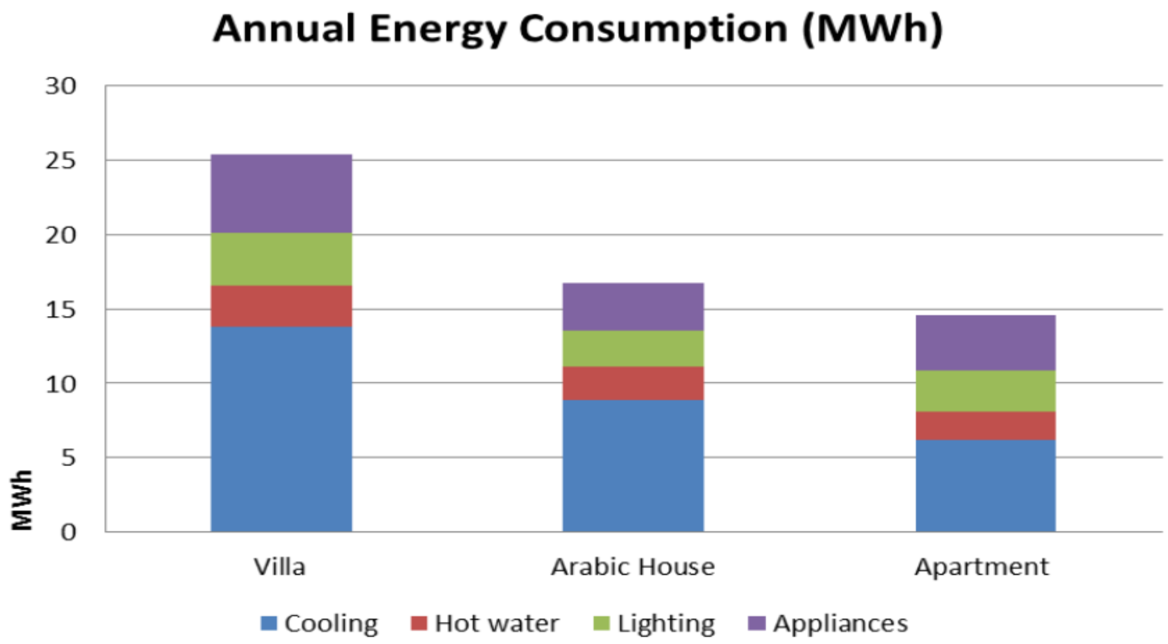


Figure 4.6: Residential typology energy consumption classification

(Source: Sweetnam, 2017)

4.3.1 Characteristics of the energy consumption of residential buildings

The household energy requirements for thermal comfort, hot water, clean clothes and other services are the fundamental drivers of the energy demand (Brounen, Kok and Quigley, 2013), (Lillemo, 2014). Understanding consumer life patterns illustrated energy-usage behaviours that contributed to the reduction of the total and peak energy demands (Krane, 2015). The UCL Energy Institute report provided three distinct energy consumption profiles. The energy profiles for these three different periods were similar but their magnitudes were different (Figure 4.7). Their similar profiles indicated that the occupant's usage of home appliances was the same in summer and winter but that the use of air conditioning devices resulted in the difference in magnitude.

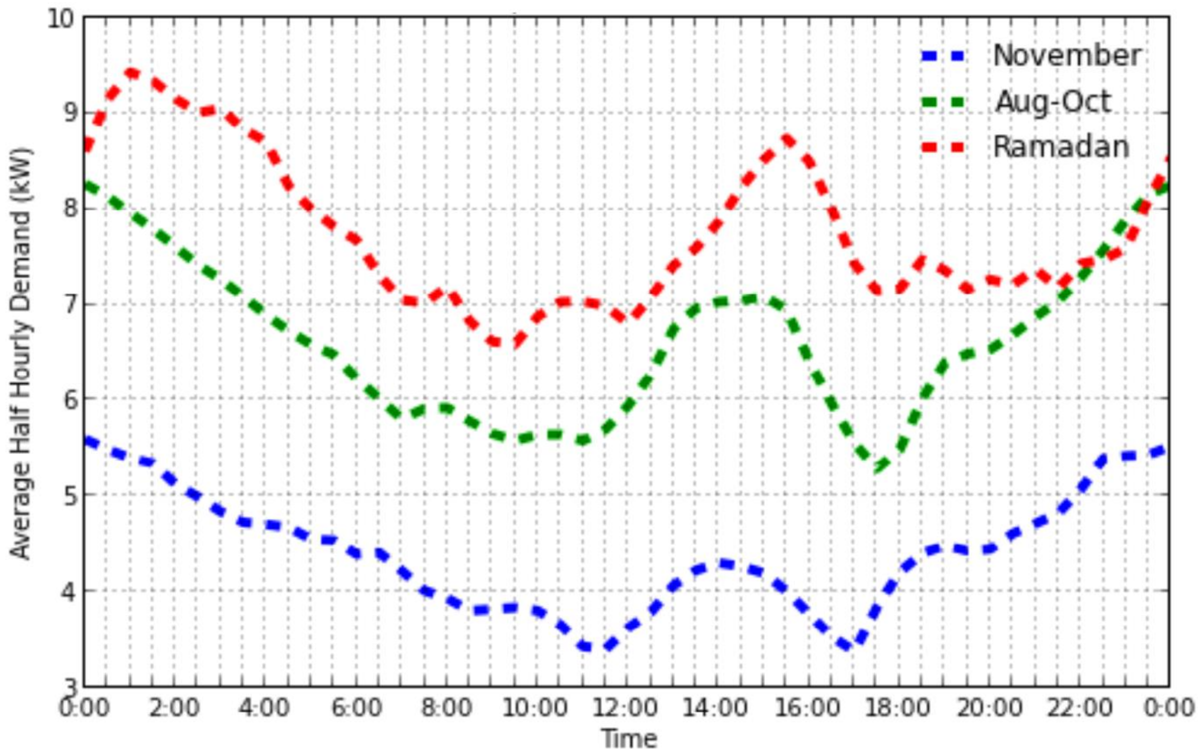


Figure 4.7: Daily energy demand profile for Omani houses

(Source: Sweetnam, 2017)

4.4 Public awareness of sustainable residential buildings in Oman

Residential buildings sector in Oman consume a significant amount of energy compared to other main energy consumer sectors (Figure 4.8) and this set to increase in the future if the public remains unaware about the country's current energy status and sustainable alternatives for energy use in buildings. In fact, the public are still not aware of the overall energy status of the country, bearing in mind, that Oman oil and gas productions are generally lower than other GCC countries with higher production cost and dwindling oil reserves. Education and training programmes, labelling schemes and smart metering are all initiatives based on the principle that additional and better information will encourage the public to use less energy. However, even with these actions, the energy consumption of buildings is projected to increase in the future (GSA, 2011; EIA, 2014) based on utilities' expectation of increased electricity demand by 9% per annum until 2021 (Projections of the future power and water system in Oman, 2017). Therefore, a more comprehensive approach is required in order to make real lasting improvements. Raising public awareness of the sustainability of residential buildings is one of the recommended policies used in order to implement energy saving strategies (Lillemo, 2014). This is due to the fact it is not buildings that consume energy, but the way in which users operate the building (Sweetnam, 2017).

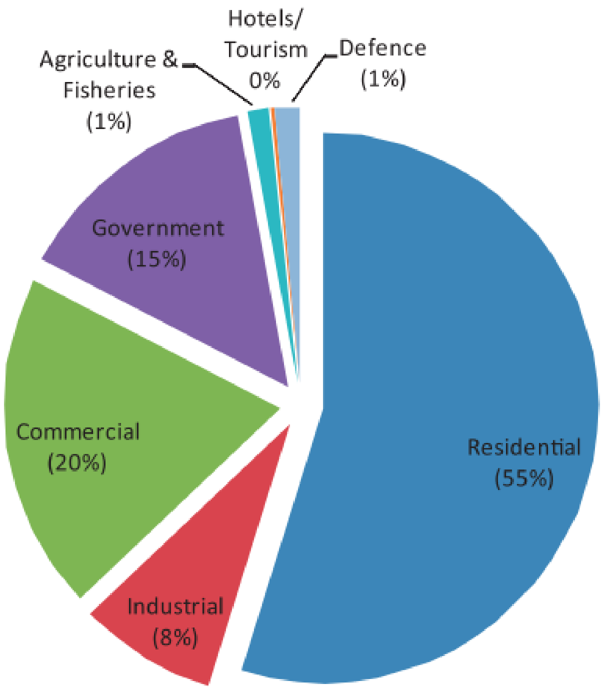


Figure 4.8: Energy consumption per sector

(Source: Al-Badi, Malik and Gastli, 2011)

The concept of sustainable buildings is still new to the Omani building industry, and the public is not fully aware of the sustainable building principles and practices (Majid, Shuichi and Takagi, 2012). This can be understood from the society's attitude towards current energy practice in residential buildings in particular (Sweetnam, 2017). The decisions of local people are always taken based on criteria that do not consider energy consumption when purchasing new home appliances (Brounen, Kok and Quigley, 2013). The main features that consumers look for in home appliances are trademark and price. The consumer cannot identify the potential of any savings on the basis of the acquisition of more efficient technological equipment. Moreover, most householders switch on their air conditioning when required, but they do not turn it off when they leave the rooms even for longer periods of time (Figure 4.9). Similarly, in the case of lights and other home appliances, the occupants may leave them on while these are not in use. In the absence of real incentives, the public are more likely not to consider implementing fundamental energy saving measures, such as turning off lights and appliances when they are not in use.

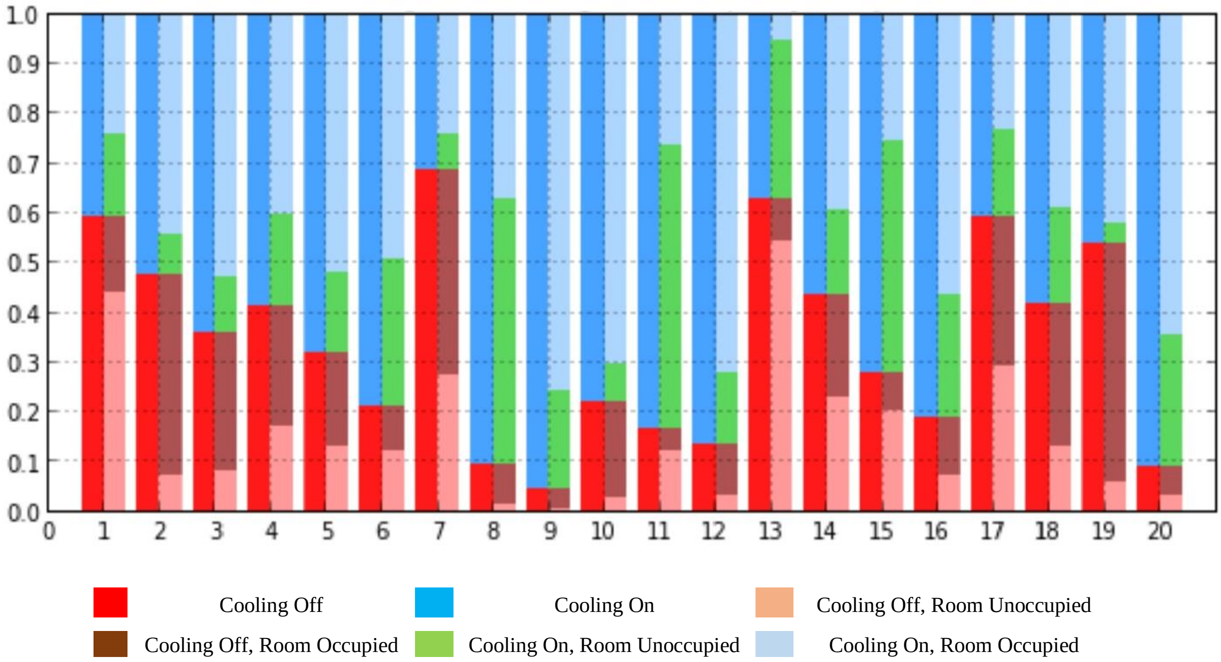


Figure 4.9: Summer air conditioning usage in a typical Omani house

(Sweetnam, 2017)

4.4.1 Impact of occupant behaviours on the energy consumption

The energy usage of a building is not only affected by the occupant's behaviour but by cultural variables such as lifestyle, age, gender, health condition and level of physical activity (Table 3.3) (Majid, Shuichi and Takagi, 2012). This can be observed from the differences in air-conditioning set points, lighting levels, hot water temperatures demanded and the number of electric and electronic devices or plug loads in use (Alalouch, Saleh and Al-Saadi, 2016). Building regulations in Oman state that the design of Omani houses should respect the Muslim Arab culture (Soheir Mohamed Hegazy, 2015). So most Omani houses include a male sitting room and a separate sitting room for females. A typical Omani home is designed to offer family members a high degree of privacy, e.g. a four-bedroom house normally includes three separate toilet/bathrooms in order to provide sufficient privacy within the house in addition to separate toilets for both sitting rooms (Figure 4.5). This culture of privacy increases the energy consumption of the building by increasing the total building area that consequently requires more energy to condition and illuminate as well as for circulation area. Cultural behaviours should be respected but their negative impact on energy requires optimisation when designing buildings.

4.4.2 Occupant comfort and well-being requirements

The discipline of well-being or thermal comfort pertains to the notion of a comfortable environment (Fabbri, 2015). This concept became widely used in the twentieth century after it became possible to directly control the microclimate of the indoor spaces (Fabbri, 2015). Since the HVAC system is the largest single energy user in Omani dwellings occupant comfort and wellbeing in the house affects the energy usage behaviours and influences the total and peak energy demand.

ASHRAE Standard 55 states that comfort is the condition of mind that expresses satisfaction with the thermal environment assessed by subjective evaluation (ASHRAE 2004). The ANSI/ASHRAE standard 55 sought to assist the industry and the public by offering a uniform method for testing and evaluating thermal comfort for rating purposes. The standard specifies "acceptable conditions by the majority of a group of occupants exposed to the same conditions within a space" (Olesen & Brager, 2004). The "majority" is in this instance was defined by an 80% overall acceptability, whereas the specific discomfort limits vary for different sources of local discomfort. The acceptable range for indoor temperature are defined by the indoor operative temperature and mean monthly outdoor air temperature. They are based on the comfort equation for naturally conditioned buildings derived from ASHRAE RP884:

$$T_{comf} = a\ T_{out} + b \qquad \text{Eq. 3.1}$$

Energy efficiency of building refer to its ability to operate with minimum energy consumption, and if comfort is a prerequisite for human, then building need to provide required degree of comfort with less energy use. Understanding and influencing occupant behaviour has the potential to deliver cost effective energy savings.

4.5 Future trends in building energy consumption in Oman

No energy conservation practice exists in the country and the demand for electricity is increasing and the main indicators for this increase are listed as follows:

- The annual energy consumption is growing faster than the population (9% vs. 1.4%) (Oman energy report, 2013). The energy consumption per capita has increased by

11.18% in 10 years because of the improvement of the comfort level and the extension of human activities (OPWP's 7-Years Statement, 2012).

- The electricity consumption in residential buildings increased from 9% to 48% of the total electricity consumption on a national level (Energy trends, 2009).
- The economic factor is also a definitive parameter in the energy consumption increase (Qader, 2009) where the GDP of Oman is growing by about 4.4% per year (List of countries by real GDP growth rate, 2017), which directly influenced the total final consumption (Magazzino, 2016).

Moreover, life pattern changes in the last four decades mean that homes are expected to consume more energy in the future due to the absence of an energy conservation or reduction plan (Figure 4.10). This also indicates that future Omani houses are unlikely to meet the low-carbon requirements of the best practice LCB (table 3.3). Hence the need for a national energy plan includes the adoption of low-carbon residential buildings in order to maintain a sustainable future for the country. Nevertheless, current low-carbon building practice in Oman faces challenges and falls below international levels (table 3.2) (Alalouch, Saleh and Al-Saadi, 2016). To develop state of the arts solution for deficiency of efficient energy home in Oman, a good low-carbon building practice should prompt the international hierarchy of low-carbon buildings to take into consideration the overall social/economic status of the country. Moreover, life pattern changes in the last four decades mean that homes are expected to consume more energy in the future due to the absence of an energy conservation or reduction plan.

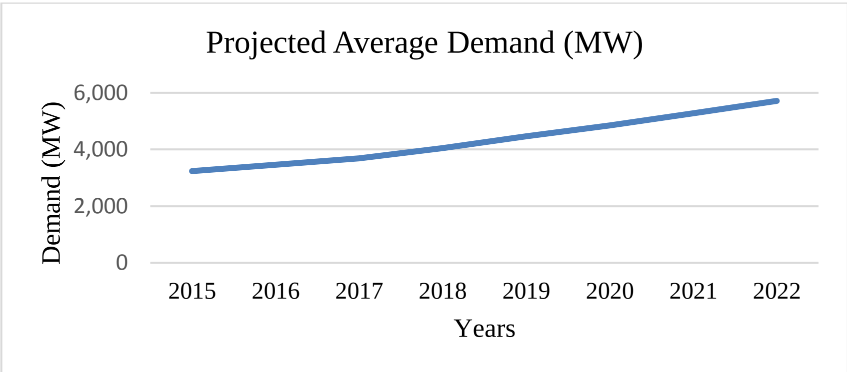


Figure 4.10: Projected future electricity consumption in Oman

(source: OPWP ' s 7 – Years Statement, 2016)

4.6 Main barriers to the widespread adoption of low-carbon building in Oman

The barriers that hinder the adoption of any energy saving policies in Oman is not a new topic of debate and many researchers have classified these barriers into groups, dependent on the methodologies used in their research (Table 4.4).

Publication	Date	Researcher	Barrier classification
Overcoming social and institutional barriers on energy conservation	1980	Blumstein et al.	Misplaced incentives, lack of information, regulation, market structure, financing, customs
Closing the efficiency gap: barriers on the efficient use of energy	1990	Hirst and Brown	Structural and behavioural barriers; institutional, market, organisational, and behavioural barriers
Some reflections on the barriers on the efficient use of energy	1997	Weber	Barriers imposed by political institutions, obstacles conditioned by the market, barriers within organisations
Energy saving by firms: decision-making, barriers and policies	2001	Groot et al.	Not enough importance given to energy costs), “low priority (efficiency” and, the existence of “other priorities”)
A preliminary inquiry into why buildings remain energy inefficient and the potential remedy	2002	Yik and Lee	Knowledge, financial, and motivation barriers
General wisdom concerning the factors affecting the adoption of cleaner technologies: a survey 1990–2007	2008	Montalvo	Depending on the circumstances, time, and contexts in which they were considered
Barriers' and policies' analysis of China's building energy efficiency	2013	Yurong Zhang	Legal system, administrative issues constitute major barriers, and the lack of financial incentives and the mismatching of market mechanisms, hamper the promotion of building energy efficiency.

Table 4.4: Barrier classification in the literature

Furthermore, some researchers incorporated survey studies and questionnaires in order to analyse these barriers. In most cases, building sector practitioners were divided into several groups, for example architects, contractors, users and energy professionals. Hence, some studies focused on specific target groups while others conducted their analysis through comparative studies.

In all the reviewed research studies, their barriers and context refer to the environment, regulatory bodies and framework, and ultimately the social and economic standards of the country. Based on this, and the nature of Oman, the barriers preventing the widespread adoption of low-carbon buildings in Oman can be classified into the following groups: -

- **Environmental:** Including current weather conditions and impact of climate change on energy use of future buildings.
- **Social and cultural:** Including the existence of social and institutional structures that limit the dissemination and cultural incorporation of this practice.
- **Limited awareness of energy saving** including public participation.
- **Economic barriers:** Such as lack of available LCB technologies, funding or financing difficulties and limited support.
- **Limited government and technical drivers:** Including the absence of rules, regulations and guidance documentation, limited policy framework and strategic planning, funding or financing difficulties and limited action to exploit renewable energy sources.

In this context, it is important to emphasise that some barriers are possible to resolve with less additional cost such as public awareness, while other barriers require substantial changes in residential building design concept.

4.6.1 Environmental barriers

Environmental barriers including current weather and climate changes, are considered important barriers against the widespread adoption of low carbon buildings in Oman. Weather conditions play a major role on building energy usage as heating and cooling energy demands are directly affected by environmental temperature and humidity. The share of energy consumption dedicated to achieving thermal comfort criteria (heating and cooling) is substantial and ranges from 55% to 74%, depending on the climatic region (Santos *et al.*, 2011). It is well known that providing thermal comfort in hot humid climates such as Muscat (Figure 4.11) is difficult to achieve by natural means and requires mechanical systems to provide the required range of comfort (Al-Hinai, Batty and Probert, 1993).

Climate data for Muscat													
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Record high °C (°F)	34.6 (94.3)	38.2 (100.8)	41.5 (106.7)	44.9 (112.8)	48.3 (118.9)	48.5 (119.3)	49.1 (120.4)	49.2 (120.6)	47.2 (117)	43.6 (110.5)	39.4 (102.9)	37.8 (100)	49.2 (120.6)
Average high °C (°F)	25.5 (77.9)	26.1 (79)	29.8 (85.6)	34.7 (94.5)	39.5 (103.1)	40.4 (104.7)	38.6 (101.5)	36.2 (97.2)	36.3 (97.3)	35.0 (95)	30.5 (86.9)	27.1 (80.8)	33.31 (91.96)
Daily mean °C (°F)	21.3 (70.3)	21.9 (71.4)	25.2 (77.4)	29.8 (85.6)	34.2 (93.6)	35.2 (95.4)	34.3 (93.7)	32.0 (89.6)	31.4 (88.5)	29.7 (85.5)	25.7 (78.3)	22.6 (72.7)	28.61 (83.5)
Average low °C (°F)	17.3 (63.1)	17.6 (63.7)	20.7 (69.3)	24.7 (76.5)	29.1 (84.4)	30.6 (87.1)	30.4 (86.7)	28.4 (83.1)	27.5 (81.5)	24.9 (76.8)	20.9 (69.6)	18.9 (66)	24.25 (75.65)
Record low °C (°F)	1.6 (34.9)	2.3 (36.1)	7.0 (44.6)	10.3 (50.5)	17.2 (63)	21.6 (70.9)	23.5 (74.3)	21.3 (70.3)	19.0 (66.2)	14.3 (57.7)	9.4 (48.9)	4.5 (40.1)	1.6 (34.9)
Precipitation mm (inches)	12.8 (0.504)	24.5 (0.965)	15.9 (0.626)	17.1 (0.673)	7.0 (0.276)	0.9 (0.035)	0.2 (0.008)	0.8 (0.031)	0.0 (0)	1.0 (0.039)	6.8 (0.268)	13.3 (0.524)	100.3 (3.949)
Average humidity (%)	63	64	58	45	42	49	60	67	63	55	60	65	57.6
Mean monthly sunshine hours	268.6	244.8	278.3	292.5	347.4	325.7	277.7	278.6	303.9	316.9	291.9	267.0	3,493.3

Figure 4.11: Muscat weather data

(Source: Muscat, Oman, 2017)

Researchers anticipate that climate change may seriously affect the energy consumption of buildings by increasing their air conditioning loads (Lam *et al.*, 2010). Wan *et al.*, predicted that the annual building energy use in air-conditioned office buildings in Hong Kong at the end of 21st century likely to increase by an average of 6.6% to 8.1% more than its values in 1979–2008 due to climate changes (Wan, Li and Lam, 2011).

4.6.2 Social/cultural barriers

Socio-cultural barriers largely prevent the spread of energy efficient domestic buildings in many countries. A study carried out in Liaoning, China investigated the barriers to energy efficiency for domestic buildings, and identified the patterns of the occupants' consumption of electricity as one of the main barriers (Dianshu *et al.*, 2010), (Observer, 2017). In addition, more studies considered that occupant behaviours and culture are one of the significant factors that control the energy consumption in homes (Virote & Neves-Silva, 2012; Hendrickson & Wittman, 2010; Romero *et al.*, 2013), (Al-Badi, Malik and Gastli, 2011), (A Review of Sustainable Design in the Middle East, 2017), (Al-Badi, Malik and Gastli, 2011).

Some occupant behaviours are related to cultural attitudes such as the separation of male sitting rooms from female sitting rooms in Oman while other behaviours are related to a limited knowledge by the public (Sweetnam, 2017). For an example, the public in Oman believes that the energy source implies national wealth and that they have the right to consume as much as they need from this source without any restrictions (Qatar Financial Centre (QFC) Authority, 2010). These attitudes lead to a society that pays little or consideration to energy conservation in residential buildings, that is subsequently reflected in an increased energy demand both now and in the future (Sweetnam, 2017).

4.6.3 Limited awareness of energy saving and public participation

Public awareness in terms of energy saving in buildings is a substantial factor in implementing a low-carbon strategy in a country (Huang, Mauerhofer and Geng, 2016). The awareness of the public will change the occupant's attitude towards energy conservation in the building. Consequently, the society will shift from traditional homes to energy efficient buildings (A Review of Sustainable Design in the Middle East, 2017). Traditional homes are equipped with appliances that are manually controlled by operating an on-off switch such as traditional lighting and air-conditioning. These devices have limited controls and managing the energy use can be difficult. Smart homes allow for the remote electronic control and management of smart appliances (heaters, air conditioners, washing machines etc.) and demonstrates the convergence of energy efficient appliances and real-time access to energy usage data, facilitated by a network of sensors and computers (ITU, 2010). Increasing public knowledge on energy and cost information will enable building occupants to proactively manage energy use in a cost effective and environmentally beneficial way. This will require educating the society on the negative aspects of the excessive use of energy in homes.

4.6.4 Economic Barriers (Financial and cost (marketing)

The cost and market value of a building determine its ability to compete against other options. The method used to compare building options, in terms of costs, includes the construction price and the operation costs during the whole life of the building (Motuzienė *et al.*, 2016). The life cycle cost analysis is an appropriate analytical method for building evaluation that considers the costs of construction, operation, maintenance and disposal of the building at the end of its life cycle (Fuller and Petersen, 1996). The National Institute of Standards and Technology (NIST) Handbook 135, 1995 edition (Cabeza *et al.*, 2014), defines life cycle cost (LCC) as *"the total discounted dollar cost of owning, operating, maintaining, and disposing of a building or a building system"* over a period of time.

The main concept of the life cycle cost analysis is to determine the most cost effective option from different alternatives of projects based on the whole life cycle of the project (Cabeza et *al.*, 2014), (Fuller and Petersen, 1996). For the life cycle cost of a building, the sum of the initial value (I) which represents the cost of constructing buildings including design, materials and home appliances is added to the total cost of energy operation during its life cycle (E), maintenance (M), minus the salvage value (S).

$$\text{Life Cycle Cost (LCC)} = I + E + M - S \qquad \text{Eq. 4.1}$$

In evaluating different construction options for buildings the lower LCC options are more viable for the building because the higher initial capital costs are eventually recovered by the significantly reduced annual running costs. However, if the energy cost is low and the cost of low-carbon technology is high such as in the case of Oman and in most GCC countries, then the construction of low-carbon buildings will not be economically viable and hence the LCB option would not be marketed.

4.6.5 Funding or financing difficulties

The sustainable housing concept, in general, includes in its framework rules and regulations pertaining to the provision of land, urban planning, the construction industry materials, health systems and financial funding for such housing projects (Akadiri, Chinyio and Olomolaiye, 2012). Due to the nature of Omani economies, a sustainable housing implementation requires strong support from the public, government and the housing industry (Al-Badi, Malik and Gastli, 2011). Under these circumstances, governmental support in terms of attracting private funding is necessary in order to implement green building projects. Financial funds for low-carbon buildings will reduce the difference in the total cost between energy efficient buildings and conventional buildings that helps the proliferation of this type of building in the country and increases their environmental benefits (Alalouch, Saleh and Al-Saadi, 2016). This can be achieved through the provision of financial or technological support for the use of renewable energy or through low-interest lending programmes to reduce the high initial cost of this type of construction (Al-Badi *et al.*, 2009).

4.6.6 Limited governmental and technical drivers

Many studies have indicated that the regulatory system and environmental assessment procedures are necessary to construct low-carbon buildings (Kajikawa *et al.,* 2011; Gou and Lau, 2014). In developed countries, the policies relating to building energy are moving quickly toward regulatory levels that are close to zero energy. Some developed countries have established a regulatory target for a zero-net carbon aimed to achieve a substantial reduction of the overall energy consumption. Building regulations is one policy aspect addressing both climate change and energy security (Murphy, 2012).

At present, there is an increasing concern in both developing and developed countries, towards employing building energy regulations and standards in order to minimise the negative impact of the energy consumption of buildings (Vine, 2003, Iwaro and Mwasha, 2010; Radhi, 2009). Low-carbon building regulations act as drivers within the construction industry seeking to reduce the energy consumption of buildings and CO_2 emissions. The absence of these laws indicates that the construction sector is not committed to the implementation of the energy conservation policy. Currently, there are no such regulatory frameworks in Oman for low-carbon buildings (Alalouch, Saleh and Al-Saadi, 2016). Hence, most residential buildings lack the required LCB techniques such as appropriate orientation or shading devices (Alalouch, Saleh and Al-Saadi, 2016). The building regulations for Muscat focus on building materials, areas and the dimensions of the rooms (Local Order No. 23/92 Building Regulation for Muscat, 1992). It states that the architectural design of the building should conform to the social norms of the Arab Muslim families. Privacy within the residential unit should be maintained regardless of whether the building consists of a single residential unit or multi-floor apartments. For example, the main entrance should not be exposed or interfere with the privacy and freedom of the internal movement of the family members inside the house. The boundary walls of any dwelling, separating two residential units or separating the living room from the guest room shall not be less than 20 cm thick, in order to prevent and reduce the transmission of sound. The sizes of the bedrooms should not be less than 12 m^2 with the smallest dimension not being less than 3 m. The regulation does not provide any description of energy performance or any compulsory action to reduce the energy consumption of the building.

4.6.7 Limited policy framework and strategic planning

The government plays a critical role in prompting owners to adopt a low-carbon strategy, as they will not be comprehensively implemented without government support (Timilsina and Shah, 2016). In order to secure a sustainable future for the country, governments are responsible for the national energy strategy. The role of governments is thus to provide the required legislation and regulations and amend them periodically in order to meet the targets of a low-carbon home, and more stringently in order to achieve sustainable urbanisation (Chapman, McLellan and Tezuka, 2016). Strategic planning requires effective policies that motivate owners to implement a sustainable development. Such a strategy mainly consists of targets and a comprehensive plan to achieve the goal of this strategy. Research by Abidin and Powmya (2014), through market survey, identified the lack of governmental incentives is one of the major barriers in promoting LCB in Oman (Powmya and Zainul Abidin2, 2014).

4.6.8 Low adoption and high cost of LCB technologies & strategies

The number of efficient energy homes in Oman is very low, and this is due to the limited ability of construction firms, understanding of the public for the need for LCB and absence of support from the government (Powmya and Zainul Abidin2, 2014), (Alalouch, Saleh and Al-Saadi, 2016). Most construction firms employ small workforces and are limited in their research and development (R&D) capacity (Saleh and Alalouch, 2015). In Oman, only a few construction firms are able to deal with new materials and often exploit new construction methodology in order to reduce the energy consumption of the building to a value that is convenient to the country’s environment. For example, the five low-carbon buildings studied in this research were constructed by class (A) contractors (Saleh and Alalouch, 2015). Prominent contractors in Oman normally do not consider the construction of small projects, such as individual villas, because of the low margin of profit (Saleh and Alalouch, 2015). Hence, the construction cost of these five low-carbon buildings was relatively high compared to the construction cost of conventional residential buildings in Oman. The market survey conducted to identify the construction cost of reference buildings used in this research shows that the difference in construction cost of some reference LCB compared to conventional building is more than 100% (Table 4.5).

	Reference building	average construction price OR (£)	Area (m^2)	price /m^2 OR (£)
Low carbon building	Dhofari Eco-House (LBC1)	125,000 (250,000)	324	386 (772)
	GUTech Eco house (LBC2)	150,000 (300,000)	257	584 (1168)
	HCT GreenNest (LBC3)	130,000 (260,000)	287	452 (904)
	SQU House (LBC4)	115,000 (230,000)	354	325 (650)
	BUSTAN OMAN (LBC5)	155,000 (310,000)	346	448 (896)

Table 4.5: Summary of market survey on construction cost of reference LCB

4.6.9 Lack of research support

The lack of research support is one of the challenging factors threatening the successful application of sustainability in Oman as, to-date, there are no research centres in the country focusing on the building environment (Saleh and Alalouch, 2015). This demonstrates a severe shortage of research and development in this field. In addition, as explained in the previous section, none of the leading construction companies intend to support research in sustainable construction. This can be linked to the absence of the drivers required to establish such research support. In addition, local academic institutions have not expressed interest in researching low-carbon buildings for the climate and environment of Oman (Powmya and Zainul Abidin, 2014).

4.6.10 Limited action on use of renewables

Many countries have implemented selected policies for renewable energy development ranging from setting power purchase agreements and the legislation of renewable energy requirements to providing incentives and imposing carbon taxes (Chang, Fang and Li, 2016). The data provided by The Research Council on the 5 eco-houses recently constructed in Oman shows their ability to produce energy from PV panels more than their annual requirements (Live Data – EcoHouse Design Competition, 2017). Despite of this promising available renewable resource, the country faces limited action in exploiting any renewable energy in building. The housing sector faces challenging obstacles such as high initial costs, limited local financial resources and low return rates. The construction industry will be reluctant to incorporate renewable source in building in the absence of action from a regulatory body. In addition, the lack of a comprehensive safety regulatory framework that provides the required technical guidance acted as a technical barrier to using new technology. For an example, the 50 kW solar panels installed on the Majan Electricity Company (MJEC) building recently were removed for safety reasons (Al Shibli, 2016).

4.7 Roadmap for Oman’s low-carbon buildings strategy

A successful energy efficiency policy requires the right incentives from all parties to support the markets supply chains for the residential buildings sector in order to deliver improvements in the energy conservation (Chapman, McLellan and Tezuka, 2016). This policy needs to involve and address the role of each party of the residential household in order to ensure for the success of the policy objectives. Thus, it is sought to inform policy-makers, energy firms and civil society actors by showing how different parties could contribute to a low-carbon energy future (Saleh and Alalouch, 2015).

In terms of reducing building energy consumption, it is important to consider the impact of possible futures in terms of use and climatic conditions. This initially suggests the identification of the level of low-carbon practice that the country is aiming to achieve, and solution to the main obstacles (Table 4.6). Then, a roadmap for Oman’s low-carbon building strategy needs to be devised in order to maintain energy security, contribute to economic prosperity and ensure the affordability of energy services. In this regard, the main elements of low-carbon buildings for the environment of Oman need to be addressed and evaluated in order to determine a possible target thereof. Based on the assessments of the key elements of the low-carbon that are technically viable, a master plan for the country can be drafted to include economic feasibility, social awareness, legislation and technical issues. Therefore, the contribution to knowledge of this research aims to device a residential building energy template to evaluate the effectiveness of different techniques and low-carbon building strategies that could lead to promising results, and highlight the challenges posed for different stakeholders.

Barriers	Suggested solution
Weather and climate changes challenges	Formulation of codes, climate adaptive design, use of renewable energy
Social/cultural barriers	Introduce culture of LCB in the society, increase public awareness and participation
Economic Barriers	Provide funds to motivating owners to implement sustainable development
Limited governmental and technical drivers	Provide the required legislation, and technical support.

Table 4.6: Suggested solution to the main barriers

4.7.1 Weather and climate changes challenges solutions

To explore the potential solutions for weather challenges, the required policy need to identify climate adaptive design options considering how design might respond to projected climate changes. Likewise, creating an architectural culture in the construction industry in Oman that aims to extend the adoption of low carbon building in the hot humid climate. It is expected that global warming would lead to more uses of air conditioning in hot climates, which subsequently leads to the use of more energy in building that will lead to increase of global warming (Guan, 2011). Since residential building cooling energy requirements depend strongly on local climate conditions therefore it need to be designed to coop with the future climatic conditions. A typical building service life is considered more than 50 years, hence cooling energy requirements of currently constructed buildings are required to consider impact of global warming (Chen, Wang and Ren, 2012). One of the issues that building society need to consider in formulation of codes is a climate adaptive design and emphasize the use of renewable energy in the code.

4.7.2 Social/cultural barriers

There is a general lack of awareness of the positive benefits of LCB's within the construction sector in Oman where the market demand does little to motivate owners to shift to sustainable building (Powmya and Zainul Abidin2, 2014). To counter this, the government was required to introduce several instruments to drive the development of energy efficient buildings (Al-Badi, Malik and Gastli, 2011), (Powmya and Zainul Abidin2, 2014). In order to enhance the awareness of the general public on the advantages of LCB, the government has to focus more on showing the market and the public its intentions to shift to the LCB. In this regard, an action plan is needed to create local low-carbon community service building exemplars that are used daily by the public such as mosques and schools. Currently the society is not fully aware of successful low carbon technologies on Oman, hence, creating low carbon community buildings is expected to encourage the private developer of residential projects to respect government decisions and consider low energy building alternatives. Public education and awareness are recognised as the most promising approach to conserve energy base on people decisions to protect the environment (Suryawanshi and Jumle, 2016). Hence, this will be another initiative can be carried out in this regard by raising the level of awareness in terms of sustainability in schools and universities. On the other hand, providing training workshops for the construction sector will improve market awareness (Energy Efficiency in Buildings Workshop, 2011).

4.7.3 Economic feasibility

Economic feasibility is the most critical factor and it is positively correlated with the adoption of a low-carbon strategy from the owner's perspective. This is consistent with the studies conducted in China regarding the effects of additional costs as the most significant barrier to green construction from the owner's perspective (Liu *et al.*, 2012; Shi *et al.*, 2013.). The additional costs of constructing a LCB over traditional buildings in Oman are mainly due to technologies and materials that are not available in the local market. In Oman, the cost of the currently available LCB options ranged from 325 OR to 484 OR per m^2, whereas traditional residential buildings may cost from 140 OR to 350 OR per m^2 (Economic Studies & Working Papers, 2017). This leads to a difference in prices between the two options of more than 100%, whereas Liu (2015) stated that the initial cost will increase 5% - 10% (Liu, 2015). This presents a major challenge for the use of related technologies and materials during the current rapid urbanisation. Therefore, the financial incentive policies provided by the government can alleviate the issues of higher initial investments. The Omani government has provided subsidies on energy prices especially for the residential sector. Currently, the amount of subsidies provided by the government for the electricity sector, which in the case of residential buildings their main consumption is estimated to be 67% of the cost of tariff (Al Aufi, 2016). In 2015, the support on electricity prices was OR 450 million (£ 900 million), however, this figure did not include everything, as the government sells the natural gas used to generate electricity at a subsidised price as well (Al Aufi, 2016). If this fund was directed to support the effectiveness of policies in terms of motivating owners to implement sustainable development, the latter will reduce the energy consumption of the building, and subsequently the amount of subsidies required for electricity in the future.

It is therefore, worth considering this subsidies for certified green buildings or for implementing low-carbon building technologies in order to support the prices of low-carbon building compared to conventional buildings. Another considerable measure can be used to overcome the poor economic visibility of the LCB in Oman by introducing a bilateral electricity market such as a bought in tariff where any extra energy generated by the building can be fed to the utility grid while the building owner receives financial returns. This will decrease the life cycle cost of low-carbon buildings and will increase the adoption of renewable energy (Saleh and Alalouch, 2015).

4.7.4 Limited governmental and technical drivers

The laws on energy conservation in buildings act as an effective instrument to encourage the construction industry to adopt low-carbon technologies in buildings (Powmya and Zainul Abidin2, 2014). The absence of these codes in Oman is one of the main reasons that led to the low prevalence of energy efficient buildings (Powmya and Zainul Abidin2, 2014). Therefore, in order to address this, the government should enact legislation and laws that incentivise the construction sector to follow low building energy policies. In this context, the government will need to determine the necessary specifications for low-carbon buildings that may be used to inform building laws in line with the distinctive elements of Oman. These laws include standards for the classification of green buildings, codes for the use of clean energy, laws for the quality of building materials and any other required legislation. Thereafter, these legislations should be revised periodically (Saleh and Alalouch, 2015).

Further, the comprehensive national plan for Oman needs to consider the necessary technical requirements for the transformation of the construction sector to a low energy construction industry. Currently, there is a lack of local market experience in the technology required for low-carbon buildings. For example, there are only five companies available for installing PV panels for buildings located in Muscat only.

4.8 Chapter summary

This research found that the factors leading to the non-adoption of low-carbon buildings in the Sultanate of Oman are correlated to the culture of the local society, the absence of appropriate government initiatives and support, the poor construction ability of the local construction sector and marketing difficulties due to higher initial costs that discouraged the construction sector from going further in this direction.

The culture of Omani society does not promote the idea of energy efficiency in residential buildings. This is clearly illustrated by the general social practices in the use of energy and the lack of interest in energy conservation. In addition, the role of the government in this area is almost absent due to the failure to create required laws or to provide the necessary financial support. The local market does not have the necessary technical ability or motivation to adopt a low building energy policy. The market is subjected to the commercial viability of supply and demand hence, if the demand for this type of construction remains low, the market will not consider the option.

In order to address this problem, the country requires an effective and comprehensive national energy plan that involves all concerned stakeholders. This plan should seek to raise the awareness of the society and the market, improving the economic viability of such low carbon buildings, introducing effective initiatives in order to support this trend and provide a regulatory framework in the form of codes and standards. However, before proceeding in this direction, the Sultanate must specify and practically examine the main elements of low-carbon construction in the environment of Oman for energy benchmarking. Hence, the next parts of this research will focus on this issue through the development of criteria for a residential building energy template for the Sultanate of Oman and similar environments.

5 Domestic building energy systems in Oman

5.1 Introduction

Understanding the key attributes of low carbon building is essential for developing low carbon strategies for a given climate. Climatic conditions are one of the main factors which directly affect the energy performance of buildings (Dhaka, Mathur & Garg, 2013). Multiple research approaches, including building energy monitoring and mathematical methods have been applied at associated stages of this chapter in order to provide the required theory and methods for the next chapters. In this respect, this chapter provided an illustration of the energy flow and end user consumption of energy in residential buildings by identifying the main home tasks and their associated energy usage. Then, a building energy system was established for evaluating the energy consumption of residential buildings for energy benchmarking. Furthermore, the building energy sub-system and parameter controlling demands were analysed for each home energy task. In addition, the building energy reduction measures for low carbon strategies in the hot humid climate were reviewed and the building energy profile for the energy diagnostic and energy strategy application was analysed through a case study. Finally, the key attributes for the low carbon guideline design for the hot humid climate were listed. The conclusions of the analysis determined by this chapter will be used in order to device criteria for the low carbon building template in the selected climatic zone.

5.2 Building energy system

The energy flow in buildings is needed as the basis for the energy management and analysis for the conservation policy (Nazari, Kazemi & Hashem, 2015). In this research, the analysis was performed by quantifying the energy flows with the interior of the building starting with the energy supply stage. This is often referred to as supplied energy or delivered energy. Supplied energy refers to the energy supplied from the utility company (Santamouris, 2005), while the energy losses due to the generation of energy from primary resources and the transportation of energy to the building are not accounted for in this analysis (Figure 5.1). In addition, in this research, the analysis of the building energy consumption included the renewable energy generated within the building site. The combination of these two sources together with their consumption and usage by the end consumer in the building will be referred to as the residential building energy system (Figure 5.1).

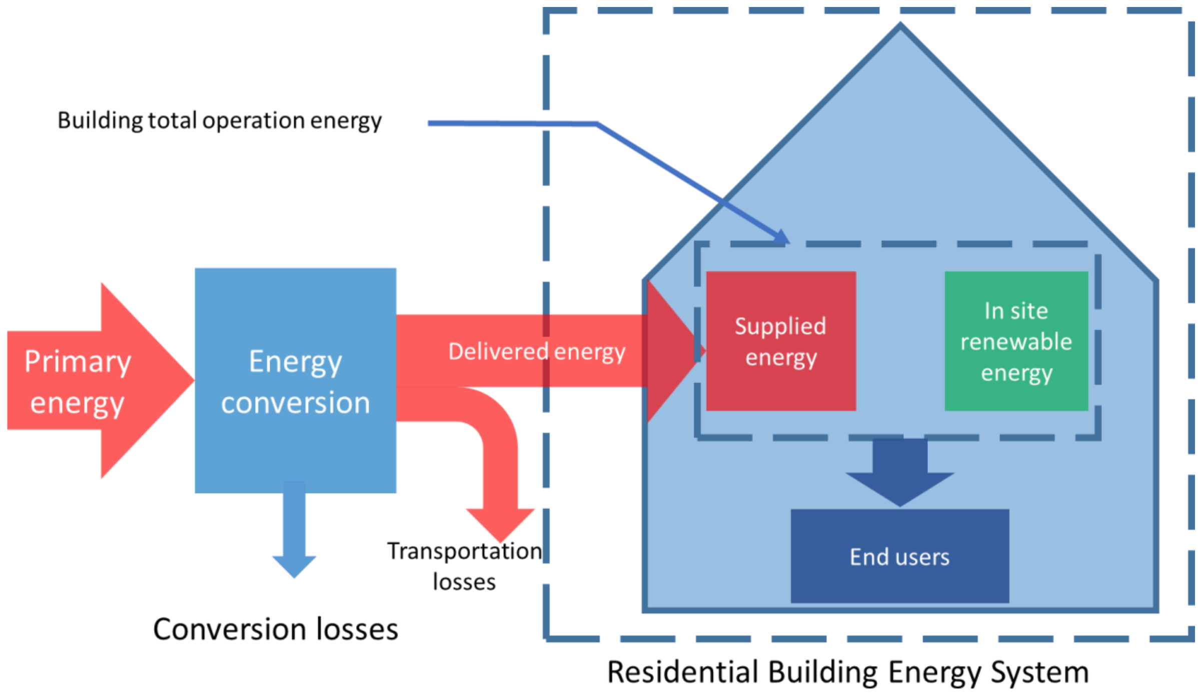


Figure 5.1: Building energy system components and boundaries

The choice of energy sources for building systems is influenced by factors such as the availability of energy sources, cost, household characteristics and the characteristics of home appliances. Since the electricity costs in Oman are relatively low, the main energy source in residential buildings in Oman is electricity with a marginal use of gas as an energy source for cooking.

The building system is referred to as “a regularly interacting or interdependent group of items (components) forming unified whole” (Vissers *et al.*, 2016). Building energy systems are analysed using top-down or bottom-up approaches. Both approaches are considered to serve as strategies for information processing and knowledge ordering, used in a number of scientific fields including software, organisation and scientific theories. In general, they are used as a style of thinking (Danielski, 2016).

A top-down model begins with a description of the overall system and is then divided into subsystems in order to understand the functioning of its different components (Wiesmann *et al.*, 2011). Conversely, a bottom-up model analyses the system by identifying its components and the interactions among its different components (Wiesmann *et al.*, 2011). In this thesis, the top-down model is used in order to describe the overall energy system of a building (Figure 4.1) and to define its boundaries and limitations. Subsequently, a bottom-up model is used in order to analyse the energy consumption of each home task (subsystem) (Figure 5.2). In the bottom-up approach, the building energy system is divided into subsystems representing individual home tasks. These tasks are identified and their energy requirements are estimated. Most bottom-up analysis models use yearly or monthly electricity consumption data. Furthermore, detailed information has been applied in some studies including the use of smart meters or data collected from monitoring (Iwafune & Yagita, 2016).

The exclusion of many small energy inputs may generate a significant truncation error. Therefore, it is important to define the boundaries and limitations of the analysed system. The boundaries act as a cut off, in which all the components outside the boundaries are excluded, while the limitations identify the applicability of the analysis (Danielski, 2016). The choice of the boundaries may affect the outcome and should therefore be clearly described. In this thesis, the boundary of the system is the energy consumption of an independent single family dwelling (Villa) in Oman. The system includes all the energy flow within the entire energy chain in the buildings, i.e. energy consumption associated with home tasks, such as thermal comfort, considered to be a sub-system for the whole energy system (Figure 5.2).

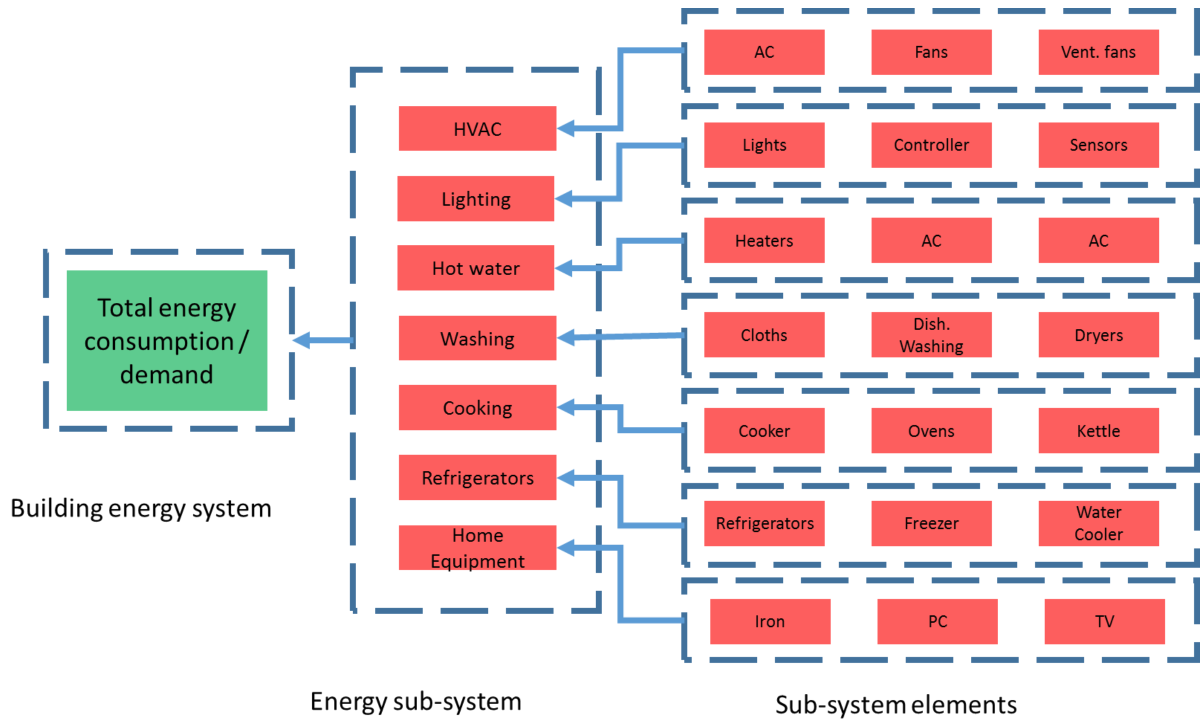


Figure 5.2: Subsystem (home tasks) arrangements

5.3 Key performance attributes of efficient low carbon building

The LCB standards were identified by comparing its energy consumption to an established reference building (baseline). The LCB contains attributes that distinguish it from the baseline building, thus leading to a reduction in its energy consumption. The key low carbon building variables analysed in this study consist of three main categories: physical features, energy system configuration and operational patterns. Each one of these categories consists of elements that contribute to the overall energy consumption either dependent on or independently from the elements from other categories (Table 5.1). This dependency relationship renders the issue of energy evaluation across buildings even more complicated.

LCB attributes	Measures for the LCB performance attributes	Relevant category		
		Physical features	System	Operation
Building design	Select the most energy efficient design likely to meet the needs of the occupants	✓		
Energy efficient	Ensure the occupants understand the energy efficient criteria and targets		✓	✓
Benchmark	Ensure the performance of buildings compared in line with appropriate benchmarks	✓	✓	
Reduce demand	Keep the energy demand to a minimum using design and services	✓	✓	✓
Operation	Keep solutions simple in order to eliminate potential failure	✓		✓
Optimise plant	Select the most efficient equipment and home appliances		✓	✓
Use effective controls	Introduce energy efficient controls which operate systems efficiently		✓	✓
Improve operation	Encourage energy efficient operation through management, maintenance and monitoring			✓
Understanding the building	Provide occupants with documents to refer to when needed	✓	✓	✓
Build for future energy efficiency	Provide opportunities for improving buildings operation if new technology is introduced	✓		

Table 5.1: Key performance attributes and variables reference categories

5.4 Building energy demand

The building energy demand is defined by the amount of energy to be provided for a building to operate at optimum capacity and functionality (Samuel, Joseph-Akwara & Richard, 2017). This requires estimating the amount of energy required and equating the energy demand of buildings to conducive living environments for the occupants. The calculated energy demand includes energy losses such as heat losses within the building envelope (Schlueter & Thesseling, 2009). Researchers proposed various methods for the evaluation of buildings' energy including:

1. Statistical analysis
2. Input–output analysis
3. Process analysis

Furthermore, in line with these methods, the energy performance analysis is classified into two types: physical calculation models and statistical calculation models (Schlueter & Thesseling, 2009). In this respect, Al-Homoud (2001) listed a number of factors to be considered when selecting the analysis method: accuracy, sensitivity, speed and cost of learning and use, reproducibility, ease of use and detail level, availability of the required date, output quality and project stage.

In real life, buildings do not use energy, but rather the occupants are the ones responsible for the energy consumption (Heywood, 2015). The occupant energy requirements at home can be summarised as: thermal comfort (TC), lighting (L), hot water (HW), washing (W), cooking (C), refrigeration (R) and electronics devices (ED). Based on this, the annual building energy demand (ABED) is equal to the summation of these energy subsystems (Eq.5.1).

$$ABED=E(TC)+E(L)+E(HW)+E(W)+E(C)+E(R)+E(ED)=kWh/y \qquad \text{Eq. 5.1}$$

Where: -

E(TC) is the annual energy consumed for thermal comfort = $\sum E_{TC}$

E(L) is the annual energy consumed for lighting = $\sum E_{L}$

E(HW) is the annual energy consumed for domestic hot water = $\sum E_{HW}$

E(W) is the annual energy consumed by wash machines= $\sum E_{W}$

E(C) is the annual energy consumed for cooking = +$\sum E_{C}$

E(R) is the annual energy consumed for refrigeration, freezers and water coolers = $\sum E_{R}$

E(ED) is the annual energy used for electronic devices and miscellaneous applications = $\sum E_{ED}$

This expression shows the flow of energy within the boundary of the system without considering the efficiency of each subsystem. The efficiency of the subsystem plays a major role in the magnitude of the total energy consumption (Wu & Zhao, 2015). Therefore, the efficiency of each subsystem (η) is required to account for the real energy consumption, and hence, the total operation energy equation (BTOE) is devised (Eq. 5.2).

$$\text{BTOE} = \frac{E(TC)}{\eta} + \frac{E(L)}{\eta} + \frac{E(HW)}{\eta} + \frac{E(W)}{\eta} + \frac{E(C)}{\eta} + \frac{E(R)}{\eta} + \frac{E(ED)}{\eta} = \text{kWh/y} \qquad \text{Eq. 5.2}$$

Furthermore, detailed subsystem components are required in order to estimate the energy usage of these home tasks and the whole building energy profile. In addition, the fundamental parameters controlling the energy consumption of each subsystem are required. Finally, the annual energy consumption of the building is generated by adding the energy requirements for each subsystem.

The level of energy efficiency in a building is measured by dividing the BTOE by the floor area of the building resulting in an energy index for the building operation (Eq. 5.3). However, the issue of energy efficiency in buildings is more complex as it varies depending on the occupancy rate of the building and on the climatic conditions (Clark, 2013). Therefore, different approaches were used for energy benchmarking in different rating systems such as Display Energy Certificates (DECs) in the UK, Energy Star in the USA and NABER Energy in Australia (Clark, 2013). All these rating systems used energy per area as a metric unit, but each tool used different adjustments for occupancy and climate. Thus, the building energy efficiency index equation had to include these factors (Eq. 4.4).

$$\text{Energy index for the building operation} = \frac{\text{BTOE}}{\text{Area}} = \text{kWh/y/m}^2 \qquad \text{Eq. 5.3}$$

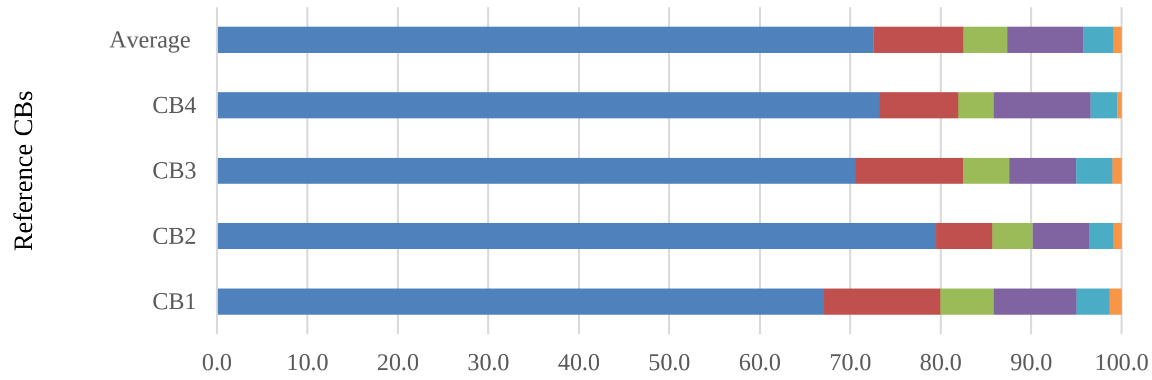
$$\text{Building energy efficiency index} = \frac{\text{BTOE}}{\text{Area x Occupancy factor}} = \text{kWh/y/m}^2 \qquad \text{Eq. 5.4}$$

Moreover, for a low carbon building index measurement, the use of available in-site renewable energy (RE) will be accounted to estimate the level of low carbon achieved by the building (Eq. 5.5).

$$\text{Low carbon building index} = \frac{\text{BTOE} - \text{Re}}{\text{Area} \times \text{Occupancy factor}} = \text{kWh/y/m}^2 \qquad \text{Eq.5.5}$$

5.4.1 Evaluation of building energy demand for thermal comfort

The energy consumption for the purpose of obtaining indoor thermal comfort in buildings on a global scale has experienced a constant growth (Dias *et al.*, 2014). According to the energy audits (Appendix A) conducted on 4 typical Omani houses within the framework of this research, the average annual electricity use for air-conditioning accounts for 73% of the total energy consumption. These results are similar for most GCC countries where researchers from Kuwait and Oman found similar values (Farraj, 2010); (Al-Hinai, 1993). It is expected to have such a large percentage of energy for cooling in Muscat, because as per the Muscat weather file the annual cooling degree-day is 6,670 compared to a zero annual heating degree-day (RETScreen, 2016). The breakdown of electricity energy usage per home task shows that lighting, refrigerators and hot water are the next sources of energy consumption after air-conditioning (Figure 5.3).



	CB1	CB2	CB3	CB4	Average
HVAC	67.1	79.5	70.5	73.2	72.6
Lighting	12.9	6.3	11.9	8.8	10.0
Hot water	5.9	4.5	5.1	3.9	4.8
Refrigeration	9.2	6.3	7.4	10.7	8.4
Washing machines	3.7	2.7	4.0	2.9	3.3
Home electronics	1.3	0.9	1.0	0.5	0.9

% Electricity consumption

Figure 5.3: Breakdown of home tasks electricity consumption for residential building in Oman

This shows that a considerable amount of energy is required for the cooling load. The cooling load is the rate at which sensible and latent heat must be removed from a space in order to maintain a comfortable environment for the occupants. Sensible heat in a given space is responsible for the rise of air temperature, while latent heat causes the rise of the moisture content (ASHRAE Handbook, 2013). The determination of the cooling load is necessary for the selection of an appropriate HVAC system in order to remove heat from the buildings' zones. A zone is typically defined as an enclosed space within a building with an area of similar heat gains and a similar control of temperature and humidity (Feng, Bauman and Schiavon, 2014). Interior heat gains usually come from three sources: heat gain through exterior surfaces, heat gain from the intake of fresh outdoor air, and heat gain generated indoors by equipment and occupants (Ding *et al.*, 2016) (Figure 5.4). Hence, the cooling loads will account for the removal of heat gains in order to reduce the internal temperature to the set point and then maintain the internal temperature at the set point. It is necessary to distinguish the difference between heat gains and cooling loads in buildings. Heat gains are defined as the rate at which heat is transferred to and generated inside the building (ASHRAE Handbook, 2013). In calculations, cooling loads and heat gains both comprise sensible and latent heat generated through conduction, convection, and radiation. Accordingly, the heat extraction rate is the rate at which heat is removed from the space by the cooling equipment (Kreider, Curtiss & Rabl, 2010; ASHRAE Handbook, 2013). Likewise, the heat gain, cooling load and heat extraction values are often not the same because of the thermal inertia effects. Thermal inertia occurred due to the heat stored in building elements and furnishers, which subsequently delayed the time at which heat gains were to be expected and extracted by the cooling equipment in order to maintain the desired indoor temperature level (Kreider, Curtiss & Rabl, 2010).

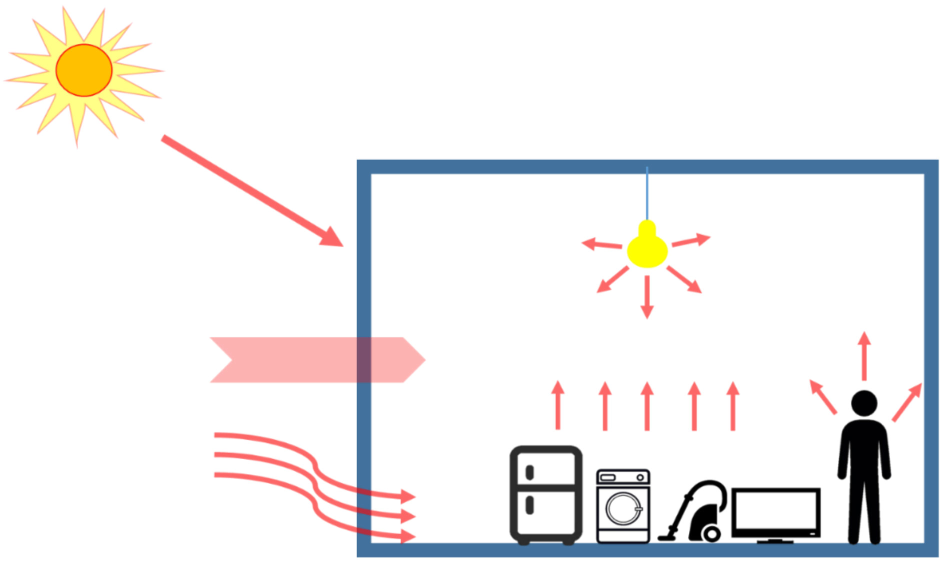


Figure 5.4: Heat gain in buildings

The thermal properties of the building envelope, lighting power density, plug load density, occupant density, indoor design arrangements and zoning, orientation, building materials and equipment efficiency are the main factors used for determining the value of heat gains in a building. In air systems, convective heat gains are directly assumed to be a cooling load.

Whereas, radiative heat gains are absorbed by walls, floors, ceilings, and furnishers causing an increase in their temperature, which will then transfer heat to the air by means of convection (ASHRAE Handbook, 2013). Finally, conductive heat gains are converted to convective and radiative heat gains. When the space air temperature and humidity reach a study state and remain constant, the heat extraction rate will then be equal to the space cooling and heat gains (ASHRAE Handbook, 2013).

Today the use of commercial software in order to calculate heating and cooling loads has simplified the process. There are various software applications available on the market and recognised by professional bodies such as the Air Conditioning Contractors of America (ACCA) for the simplicity of the HVAC design (Spitler, McQuiston & Lindsey, 1993). Regardless of the computer software design or manual calculation used in the calculation, the basic design process involves systematic steps based on the thermodynamic concept and fundamentals of heat balance.

5.4.1.1 Cooling load estimation

In the hot humid climate of Oman, the thermal comfort energy consumption ($\sum E_{TC}$) involved the energy usage for the purpose of space cooling / heating, ventilation and any other equipment used for controlling the temperature and humidity within the building zones. A fundamental and simple method used in order to estimate the heating and cooling energy demand for buildings is the degree-day method. Heating degree days (HDDs) are calculated by simple subtractions of the outdoor temperature from the base temperature, considering only positive values. The base temperature is considered as the outdoor temperature above which there is no need for a building to be heated. Likewise, cooling degree days (CDDs) are calculated from the temperatures exceeding the base temperature. In this case, a base temperature is considered as the outdoor temperature below which a building requires no cooling. The calculation of the degree days can be carried out using several methods and timescales (CIBSE, 2006):

- Mean degree hours, calculated from the hourly temperature record
- Using daily maximum and minimum temperatures
- Using mean daily temperatures

- Direct calculation of the monthly degree days from the mean monthly temperature and the monthly standard deviation

There are a few different ways of calculating the HDD and CDD, in terms of the availability of data and the integrating period. The most accurate calculation is by using hourly data ($0 \leq k \leq 24$) of the outdoor air temperature (T_i) and integrating it directly by using the base temperature (Eq. 5.6).

$$\mathrm{HDD} = \frac{\sum_{i=1}^{k} \mathrm{T}_{Hb} - \mathrm{T}_i}{24} \text{ if } (\mathrm{T}_{Hb} - \mathrm{T}_i) > 0, \quad 0 \leq k \leq 24 \qquad \text{Eq. 5.6}$$

$$\mathrm{CDD} = \frac{\sum_{i=1}^{k} \mathrm{T}_i - \mathrm{T}_{Cb}}{24} \text{ if } (\mathrm{T}_i - \mathrm{T}_{Cb}) > 0, \quad 0 \leq k \leq 24 \qquad \text{Eq.5.7}$$

Where T_{Hb} and T_{Cb} are the corresponding base temperature values for the HDD and CDD, respectively. For each month of the year, the daily values are summed giving the monthly values of the CDD and HDD and, in the process, the annual values of the CDD and HDD are estimated. For Oman, the threshold base temperatures of 27 °C and 18 °C are considered for the calculation of the CDD and HDD. The choice of these temperatures was issued by The Research Council, Oman. The weather file in Muscat shows no need for heating, however in the case of some places in Oman where heating is required, the annual energy consumption for heating E_h (kWh) for a building is calculated from the summation of HDD (Eq.5.8) (CIBSE 2006); (Kolokotroni *et al.*, 2010).

$$\mathrm{E_h} = \frac{\mathrm{U}'(\mathrm{AHDD})24}{\eta} \qquad \text{Eq. 5.8}$$

$$\mathrm{U}' = \frac{\mathrm{A.U} + \frac{1}{3}\mathrm{N.V}}{1000} \qquad \text{Eq.5.9}$$

Where: -

U' is the overall building heat loss coefficient (kW/K)

AHDD is the annual sum of HDD multiplied by 24 (hours per day) to convert to hours

η is the coefficient of efficiency of the internal heat sources ($0 < \eta < 1$)

U is the fabric U value (W/m^2K)

A is the component area (m^2)

N is the air infiltration rate in air changes per hour (h^{-1})

V is the volume of the space (m^3).

Moustris *et al.*, (2014) illustrated that the second part of Eq. (5.9) represents the natural ventilation heat losses; therefore, the numerical factor (1/3) arises from the product of the specific heat of the air C_P and the air density ρ_a. By assigning typical values, the corresponding numerical value is determined by the following calculation (Moustris *et al.*, 2014):

$$d.C_p = \left[1.2\ \frac{kg}{m^3}\right] \times \left[1.005\,\frac{kJ}{kgK} \times \frac{1}{3600} \times \frac{kWh}{kJ} \times \frac{W}{kW}\right] = 0.335\,\frac{Wh}{m^3} \approx \frac{1}{3}\frac{Wh}{m^3K} \qquad \text{Eq.5.10}$$

Similarly, the annual energy consumption for cooling (Ec) for a building is calculated as (Eq. 5.11):

$$E_c = \frac{\dot{m}C_p \times ACDD24}{COP} = \quad kWh \qquad \text{Eq. 5.11}$$

Where: -

$\dot{m}$ is the mass flow rate of the air cooled per second (kg/s)

C_p is the specific heat of air (kJ/kg/K)

ACDD is the annual sum of the CDD multiplied by 24 h day^{-1}

COP is the coefficient of performance of the cooling unit.

In case of deferent energy sources used for heating and cooling, both the annual heating energy consumption and the annual cooling energy consumption need to be converted to their primary energy consumption (PEC), to be added to the total building energy consumption. Primary energy consumption refers to the direct use at the source, or in other words the energy that has not been subjected to any conversion or transformation process (Eq. 4.12) (Moustris *et al.*, 2014).

$$PEC = E_x a \qquad \text{Eq. 5.12}$$

Where (E_x) is the total annual cooling or heating energy consumption (kWh) and (a) is the primary energy conversion factor, respectively. The PEC factor a takes different values depending on fuel. It furthermore changes with time because it depends on the generating mix in any given period.

5.4.2 Lighting requirement and evaluation

The general definition of lighting or illumination refers to the deliberate use of light to achieve a practical or aesthetic effect (Bellia & Bisegna, 2013). Lighting in buildings includes the use of artificial light sources such as lamps and light fixtures or capturing the available natural illumination from daylight. Providing proper lighting improves the appearance of an area and enhances the effectiveness of the occupants. Light fixtures are characterised by the luminous efficacy or wall-plug efficiency, which means that the amount of usable light emanated from the fixture per energy unit is usually measured in lumen (*lm*) per watt in *SI*. Depending on the context, the power can be either the radiant flux of the source's output, or it can be the total power (electric power, chemical energy, or others) consumed by the source (Boyd & Hilborn, 1984).

The energy consumption of a lighting installation is strongly dependent on lighting controls (daylight, presence detection, dimming, etc.) (Ryckaert *et al.*, 2010). The ideal method to estimate the required lighting involves subdividing the total area into the actual task area (TA) and the surrounding area (SA). The SA lighting can be reduced as much as possible (i.e., 200 lx), whereas the TA lighting is provided as per the requirement of the activities (Parise, Martirano & Di Ponio, 2013).

The uniformity of illuminance is required in both areas. In the TA it is not lower than 0.7 and in the SA it is not lower than 0.5. For example, when the illuminance maintained in the TA is recommended to be 750, 500, and 300 lx, the illuminance in the SA is recommended to be equal to 500, 300, and 200 lx. In continuously occupied areas (COAs), the recommended minimum maintained illuminance shall not be less than 200 lx. (Parise & Martirano, 2011).

In the context of this research, the procedure used to estimate the energy requirements for lighting will take into account detailed parameters that can have a significant impact. By referring to the element dedicated to lighting in equation 5.1, the annual required lighting energy E_L in kWh is calculated by the summation product of the installed power ***P(L)*** (in watts) of each luminaire, the operation time t_N (in hours), and a factor F (in per unit) that is accountable for the impact of the control system:

$$E_L = \sum \frac{E(L)}{\eta\,(L)} = \sum P_L \cdot t_N \cdot F \,/\, 1000 = \text{kWh/y} \qquad \text{Eq.5.13}$$

5.4.3 Domestic hot water requirements and its energy use

The typical uses of hot water for domestic purposes are for cooking, cleaning and bathing (Yao & Steemers, 2005). According to the CIBSE, Domestic Hot Water (DHW) is the provision of hot water distributed at approximately 50 °C for hand washing and other personnel requirements. Similarly, BS6700 stated that *"The hot water service shall be designed to provide hot water at the point of use, in the quantities and at the temperatures required by the user"*. The standard indicated that the temperature of the stored hot water should be in the range 60 °C to 65 °C.

The amount of household uses of hot water can significantly vary depending on the occupant usage attitude and requirements. Another important factor related to the hot water consumption is the rate at which water is drawn from the heating system. This is usually presented as a histogram of the consumption on a typical day (working days and weekends). Some good practice guides provide rough estimations of the amount of hot water required by a household. For example, in BSRIA's Rules of Thumb handbook it is recommended to estimate the daily consumption based on the number of bedrooms. For example, for a single bedroom, two bedrooms, three bedrooms or more bedrooms the amount of hot water should be estimated at 115 litres, 75 litres and 55 litres per bedroom, respectively. Likewise, BS6700 recommends that the hot water (60 °C) consumption of a dwelling should be estimated between 35 litres and 45 litres per person per day.

The energy usage for the DHW depends on factors including the required DHW temperature, the required volume per person, and the dwelling size (Yao & Steemers, 2005). The daily energy-consumption is calculated based on the volume of water used, in-out water temperature difference, density and heat capacity of water (Eq. 5.7) (Yao & Steemers, 2005). Hence, for the annual estimation, the value obtained from the daily consumption is multiplied by the number of days in the year (Eq. 5.15).

$$\text{Daily } E_{HW} = \frac{C_p\, \rho V\, (T_{out} - T_{in})}{3600} = \text{kWh/day} \qquad \text{Eq.5.14}$$

$$\text{Annual } E_{HW} = \frac{C_p\ \rho_w\ V_{HW}\ (T_{out} - T_{in})}{3600} \times \text{days/year} = \text{kWh/y} \qquad \text{Eq.5.15}$$

Where: -

C_p is the specific heat capacity of water (4.187 kJ/kg K)

ρ_w is the density of water (1000 kg/m^3)

V_{HW} is the daily volume of hot water consumed for each component (m^3/day)

T_{out} is the water output temperature (°C)

T_{in} is the water input temperature

5.4.4 Cold appliances energy requirements

Domestic cold appliances including refrigerators, water coolers and freezers are common home appliances that directly contribute to the total energy consumption. A device described as a "refrigerator" maintains a temperature of a few degrees above the freezing point of water (from +5 to 0 °C), whereas a device which maintains a temperature below the freezing point of water is referred to as a "freezer”. Most freezers operate at a temperature of around 0 °F (−18 °C). The use of refrigeration appliances has increased in the previous few decades in Oman. This is due to the recent changes in lifestyle which led to the use of more than one refrigerator, freezer and water cooler to be very common in Omani house.

These types of appliances are turned on for 24 hours a day and controlled by thermostat which switches the compressor on and off within the adjusted set point of refrigeration. Therefore, in the calculation of the operation energy of cold appliances, the device is considered as if it is working for a third of the time.

$$\text{Cold appliances energy consumption} = \frac{Rated\ energy}{\eta}\ 8\ \times 365 = \text{kWh/y} \qquad \text{Eq.5.16}$$

5.4.5 Household energy requirements for cooking

Cooking is one of the main energy end user in residential buildings. According to the IEA and the Food and Agriculture Organization of the United Nations (FAO), household energy use in developing countries accounts for almost 10% of the world primary energy demand. In Oman and other GCC countries, electricity and LPG gas are the main energy sources for cooking. A survey conducted in 2015 on 50 Omani families shows that a typical Omani family consumes between 10 to 16 cylinders of gas of 19 kg. In addition, the use of electrical cooking appliances has become very common.

The usage of hobs and ovens varied between different households as this depends on life style and habits. Furthermore, the number of persons in the household is the clearest indicator of usage for all appliances including cooking appliances. Therefore, the calculation of the energy used for cooking will depend on the standard functions and parameters such as the number of occupants, extent and duration of heating, use of appliances, cooking habits, etc. Hence, for the assessment of the energy usage for cooking in a regular household, the calculation is adjusted to the actual occupancy and overall energy consumption parameters.

5.4.6 Miscellaneous

The term "miscellaneous energy end user" in this thesis refers to the home appliances that are not used on a regular basis, or in other words it describes equipment that used for special purposes at random times. One procedure used in order to accurately estimate the end-use consumptions and overcome the non-negativity problem is to attach meters to the individual end-uses, enabling the direct measurement of the associated consumption over the whole period of analysis. Although this is a conceptually straightforward method, it is unfortunately not practical because the cost associated with extensive direct metering would be prohibitive. A compromise whereby some direct-metering information is available and combined with information pertaining to the occupant needs is thus required and a behavioural approach seems to be the most appropriate way to proceed.

5.5 Total load estimation and annual energy profile

The electricity demand audit can be used to generate models for the estimation of the annual energy profile. In order to estimate the annual energy demand for a building, it is necessary to list all the energy sub-systems in use (n), their energy rating (j), energy efficiency (i) and time of use (t) (Eq.5.17).

$$\text{Annual energy} = \sum(n_1 j_1 i_1 t_1) + (n_1 j_1 i_1 t_1) + \cdots = \text{kWh/y} \qquad \text{Eq.5.17}$$

5.6 Building energy performance and reduction measures

For the evaluation of the building energy performance, it is necessary to identify the level of low energy consumption required and the building energy index (BEI) in kWh/m² applicable for the country. The building energy index, sometimes known as the energy efficiency index EEI is the most commonly used index to analyse and compare the energy performance of buildings. The concept of this index is based on the ratio of energy input to the factor related to the energy usage in the building. This definition of the BEI is dependent on the parameters used as energy input and the factor related to the energy consumption. Regardless of the definition, the saving targets are always achieved through reduction measures for the building. There is no energy consumption reduction threshold at which a building qualifies as an LCB, but the energy consumption of an existing building is reduced through the configuration and operation of the energy system.

5.6.1 Reduction measures in building energy systems and operations

Energy reduction in existing buildings can be reduced by using rated home appliances and through energy management within the building. For example, it is important to reduce the energy demand for air conditioning, by using efficient non-energy or low energy cooling techniques, such as providing energy reduction measures within the building structure or proposing alternative renewable energy resources for cooling. Several such investigation studies were conducted in Saudi Arabia and have shown possibilities for achieving electricity load-levelling by means of Thermal Energy Storage (TES) in a chilled water storage/ice. It is anticipated that the TES can reduce the peak cooling-load demand by approximately 30-40% and the peak electrical demand by approximately 10-20% (Hasnain & Alabbadi, 2000). Additionally, several lighting active control strategies are available to manage the lighting energy use in buildings: scheduling, capturing daylight in buildings by windows, skylights or light shelves. Furthermore, the energy use for hot water can be reduced substantially through the use of solar heater hot water.

5.7 Energy consumption profile and measurements: A case study

A case study on energy consumption was conducted on a sample of 50 conventional residential buildings which were reviewed within the framework of this research in order to obtain the building energy consumption profile. Existing building energy data were collected by three different methods, namely a calculation-based method, a measurement-based method and a hybrid method (Wang, Yan & Xiao, 2012). The quantification of the building energy serves as the basis of any energy performance assessment method seeking to determine the amount of energy consumption or the energy performance indicators of a given building. The relevant information was collected from utility bills, building audits, end use consumer characteristics, sub-metering and monitoring systems, or computer simulations.

The methodology used in order to quantify the building energy profile in this study followed the hybrid approach where the data reviewed in this case study included the monthly electricity consumptions, building area, occupancy, location, direct sub-metering measurements, and utility referencing data. These buildings consist of three / four bedrooms, three toilets, a sitting room and a family room with a floor area ranging between 120 m^2 and 320 m^2 and occupied by Omani families constituted by 3 to 9 members. As expected, a strong correlation was identified between annual energy consumption profile and the weather conditions, where the minimum energy consumption occurred in January when the temperature reached a minimum, whereas the maximum energy consumption occurred in the months of June to August when the average temperature exceeded 35 °C (Figure 5.5); (Table 5.2).

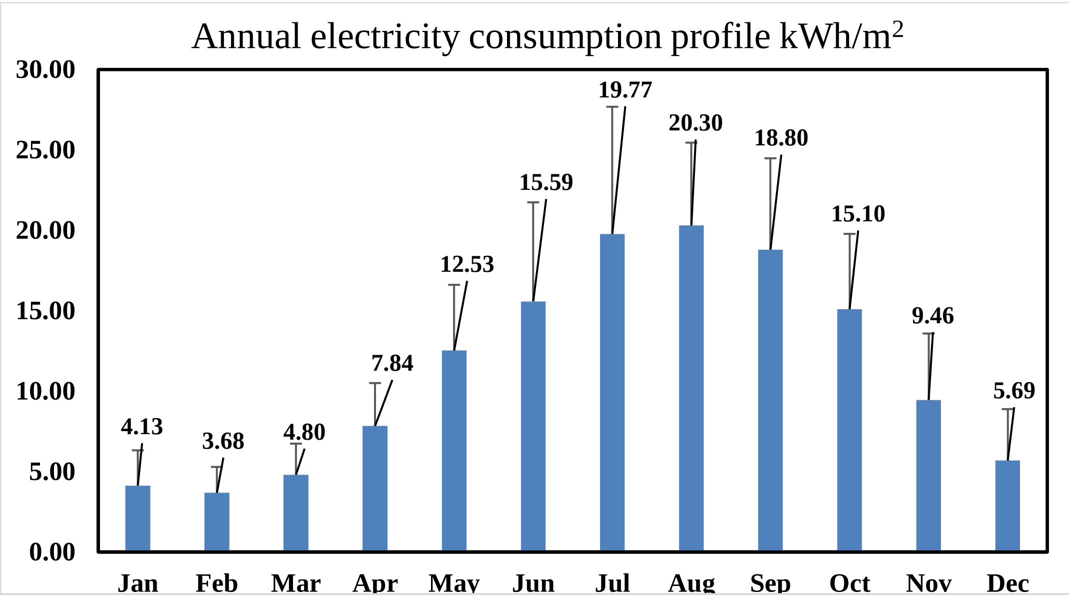


Figure 5.5: Annual electricity consumption profile for Omani residential buildings

Furthermore, a residential building energy audit (Appendix A) was conducted on four conventional buildings selected from the 50 buildings surveyed in order to provide reference data for home tasks energy consumptions and for comparing the energy consumption of these buildings to a reference low carbon building in order to examine a possible energy reduction (Figure 5.6).

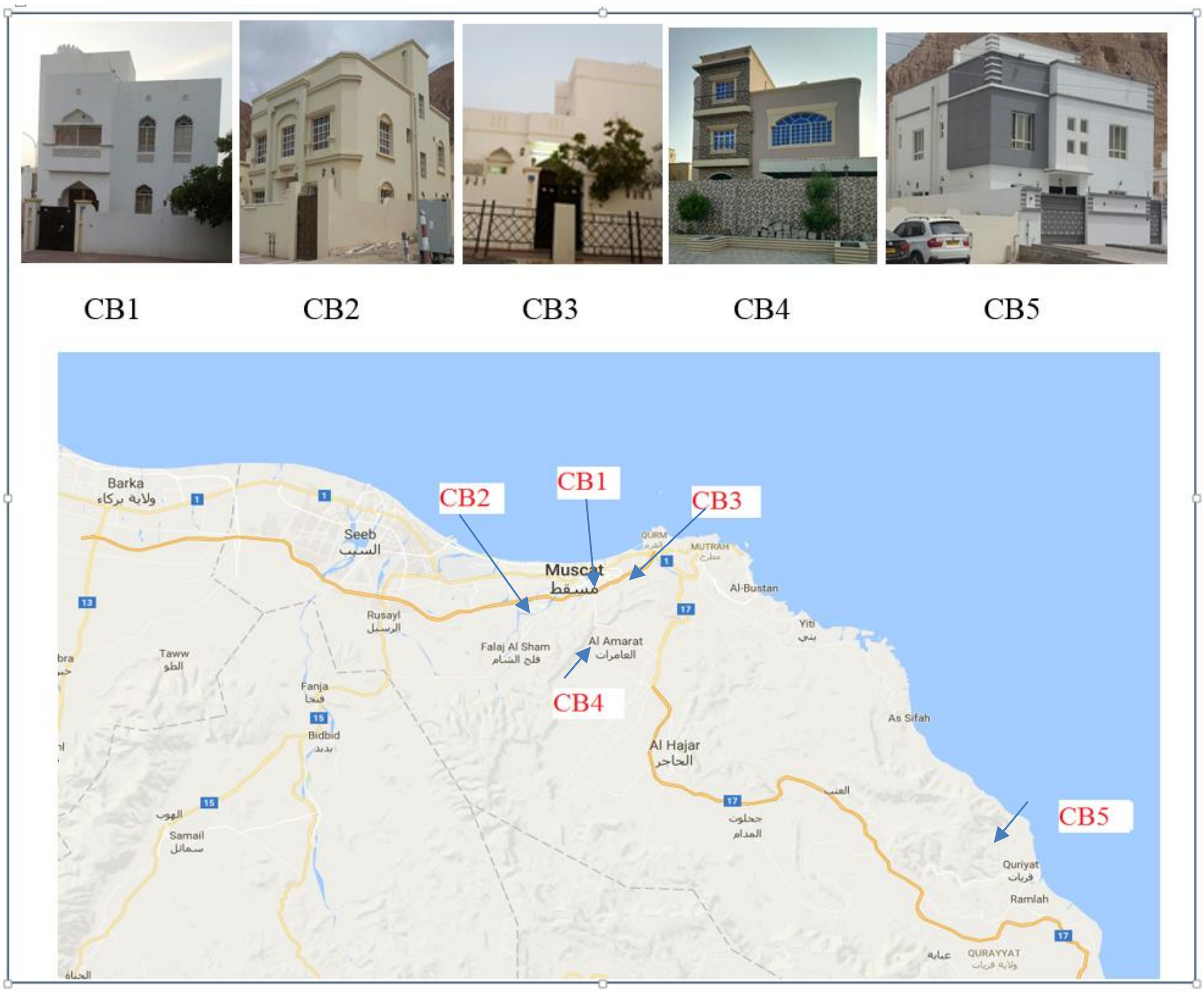


Figure 5.6: Reference conventional building location

The energy audit focused on the energy consumption for the home tasks mentioned in equation 5.1. Then, the calculated energy consumption was compared to the utility bill for the validation of the audit results and acceptable values were thus found for these buildings as they were in the range of 78% to 94% of the total energy bill for the audited month (Table 5.3). It is not possible to estimate the energy consumption of home appliances by way of calculation since their consumption may differ based on several factors including the way of use, age, power supply input and temperature of the environment. However, the results obtained from this audit are suitable as rough estimation for the establishment of the energy template in the following chapter.

	Ref. Building	CB1	CB2	CB3	CB4
	Area	212	199	240	220
	Occupancy	6	5	7	9
Monthly electricity consumption (kWh)	Jan	1047	341	1574	882
	Feb	1468	341	1515	901
	Mar	1186	353	1716	1059
	Apr	1229	693	2178	930
	May	2233	1074	3416	1037
	Jun	3811	1612	5728	1166
	Jul	4505	2463	6227	1586
	Aug	4376	2798	4001	1229
	Sep	3619	2133	3933	3368
	Oct	3738	1929	4920	1303
	Nov	1935	725	1801	1143
	Dec	1472	677	1634	935

Table 5.2: Monthly electricity consumption of four reference conventional buildings

Electricity consumption per day (kWh)				
Tasks	**CB1**	**CB2**	**CB3**	**CB4**
HVAC	67.2	161.8	103.35	65.01
Lighting	3.799	12.06	20.792	5.07
Hot water	13.2	10.8	15.6	24
Washing machine	0.214	2	1.35	0.25
Cooking	4.283	5.83	3.78	5.23
Refrigeration	7.452	9.386	8.47	11.29
H Elec.	1.011	1.505	1.14	0.455
Total daily	97.159	203.381	154.482	111.305
Calculated monthly	2914.77	6101.43	4634.46	3339.15
Monthly from the utility bill for October	3738	1935	4920	1303
Percentages calculated to actual value	77.9767	315.319	94.1963	256.266

Table 5.3: Conventional building energy audit for sample houses in Oman

These values were calculated based on the following assumption: -

I. The electricity consumption of the household calculated by multiplying the rated consumption of the appliances by the number of hours in use which may not be accurate as the consumption may differ according to the use and age of the appliances.

II. For devices with automatic on-off circuits such as water heaters, the number of working hours is estimated according to the number of users.

For calculating the carbon footprint of the operating reference conventional building (excluding transportation), an annual energy consumption report was compiled.

It can be seen that the energy consumptions by calculation are generally lower than the measured data. A comparison of the utility bills data and the calculated results shows acceptable values for CB1 and CB3 as they are in the range of 68% to 87% of the total energy bill for October. These values are assumed to be acceptable since there are miscellaneous home energy end users which cannot be estimated. These may include any home devices which were not included in the audit or unused for a period due to the presence of the family outside the house.

It is not possible to estimate the energy consumption of home appliances through calculations because their consumption may differ based on several factors, including way of use, age, power supply input, and temperature of the environment. Another factor that causes discrepancies is that the data presented by the occupants of the building show the use of the house in general over the month, when in fact, the use varies daily based on the needs and desires of the occupants. However, the results show large discrepancies for CB1 and CB4, which means the data provided by the occupants did not match the real consumption. Hence, these two buildings were excluded from the modelling analysis, but they might be considered in the energy template validation

5.7.1 Energy consumption of conventional buildings and LCBs

In order to investigate the benefits of adopting low carbon building strategies in the selected hot climates and the limitations thereof, a reference LCB was selected for conducting short-term environmental monitoring and an energy audit. In this regard, best practice low carbon buildings in the sultanate were reviewed for accessibility and suitability for this research. The benefits of the strategies applied in the selected buildings will then be mapped against a selected reference conventional building in order to identify the best strategies to be adopted. The selected reference low carbon building for this research is named GreenNest and it is located on the campus of the Higher College of Technology in Muscat, Oman (Figure 5.7). It was designed and built as part of a national competition for green buildings.

Figure 5.7: Reference LCB location

The building was designed to be net-zero energy building reliant on PV-cells in order to generate the energy required for the house. The house was designed to exchange the extra energy provided by its PVs system during daytime with the utility company and get it back when required. This design strategy saved the costs of extra batteries required in order to store the abundant electricity from the PVs (Figure 5.8).

Figure 5.8: Reference LCB3

On July, the 14th 2014 the Muscat Electricity and Distribution Company signed an agreement considered the first of its kind with the Higher College of Technology, and approved the PV system interconnecting with the local utility company. This agreement will open a new era of household energy supply in Oman provided it succeeds in this model house. The building included low carbon building measures compared to conventional buildings (Table 5.4). In addition, the site visit to the building incorporated the following features: -

- Maximised the use of climatic performance where the optimum orientation received a cool breeze in summer;
- Active means implemented through the use of an air-conditioning plant to maintain comfort in summer;
- The use of Nudura concrete which has a low U value reduced the energy consumption by reducing heat gain;
- Double glazing reduced the U value of windows;

- Solar panels located above the building to reduce the heat gain from the roof;
- Building has been zoned into two main zones based on the occupant's activities, which reduced the daily demands for space cooling;
- A ductable split unit connected to a desiccant recovery wheel (Energy Recovery Ventilator-ERV) reduced the high humidity;
- Shading provided by trees around the house and by the solar panels;
- Passive solar design;
- Insulated walls, roof and floor;
- Shading on the east side of the building;
- Energy efficient home appliances;
- LED lights.

Description of Case Study Buildings			
	Building CB1	**Building CB3**	**LCB4**
Area	212	240	220
Occupancy	6	7	3
Long Axis Orientation from the North	75° East of North	60° East of North	90° West of North
Floor Plan Shape	Rectangular	Square	Rectangle
Construction Materials	Concrete	Concrete	Nudura Concrete
% Glazing	10	17	22
External wall U Value	2.1	2.1	0.233
Internal wall U Value	2.1	2.1	0.68
Roof U Value	2.2	2.2	0.339
Floor U Value	2.5	2.5	0.568
Glazing U Value	2.7	2.3	1.9

Table 5.4: Specification of case study buildings

An online monitoring method provided by The Research Council (TRC) Oman was used, as it gives direct measurements that can be accessed remotely. The temperature and humidity measurements alongside with the HVAC power consumption are sent to the data acquisition system, which then saved it and sent it to the web page (Figure 5.9). The monitoring system consists of a data acquisition system connected to the sensors measuring the internal zone temperatures and humidity, and the electricity consumption of home appliances (Figure 5.10) (Appendix E). The recorded data was updated automatically every 20 seconds and presented in the form of an instant direct reading and a cumulative graphical form for the past 30 hours.

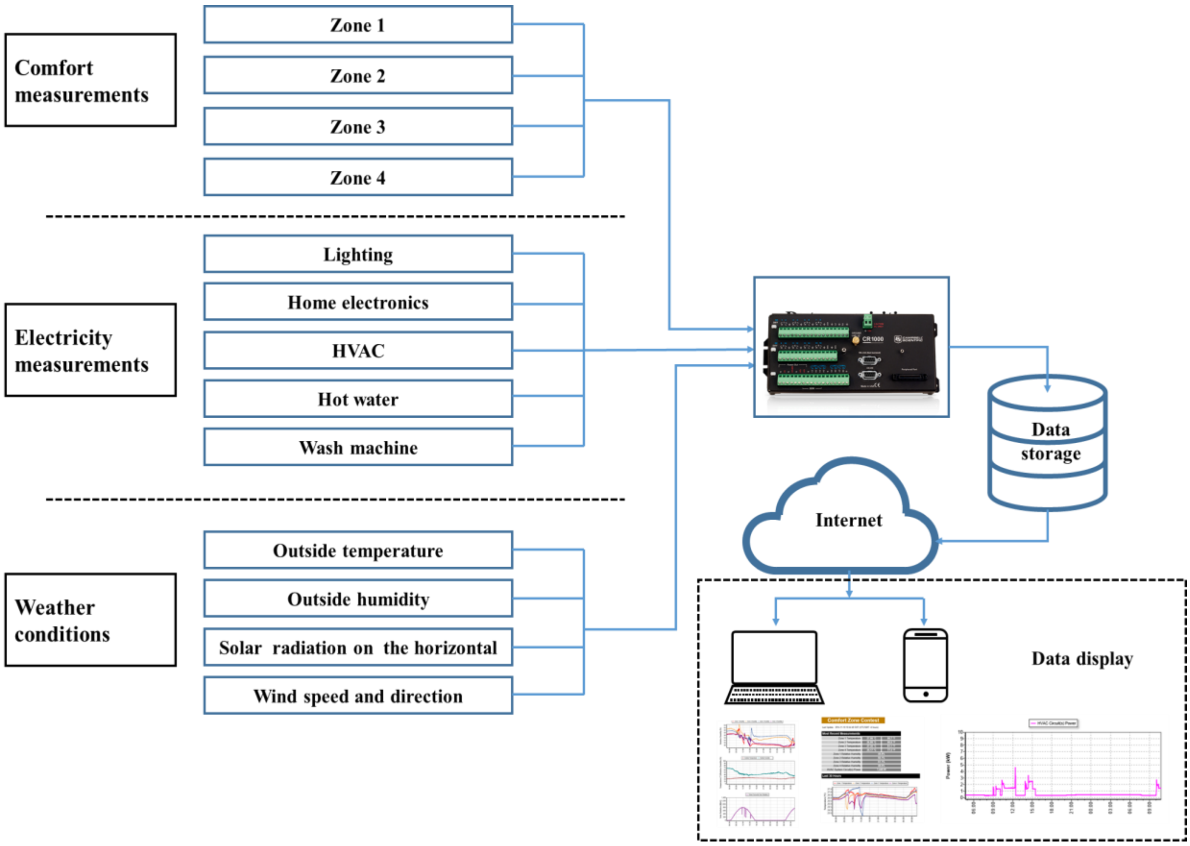
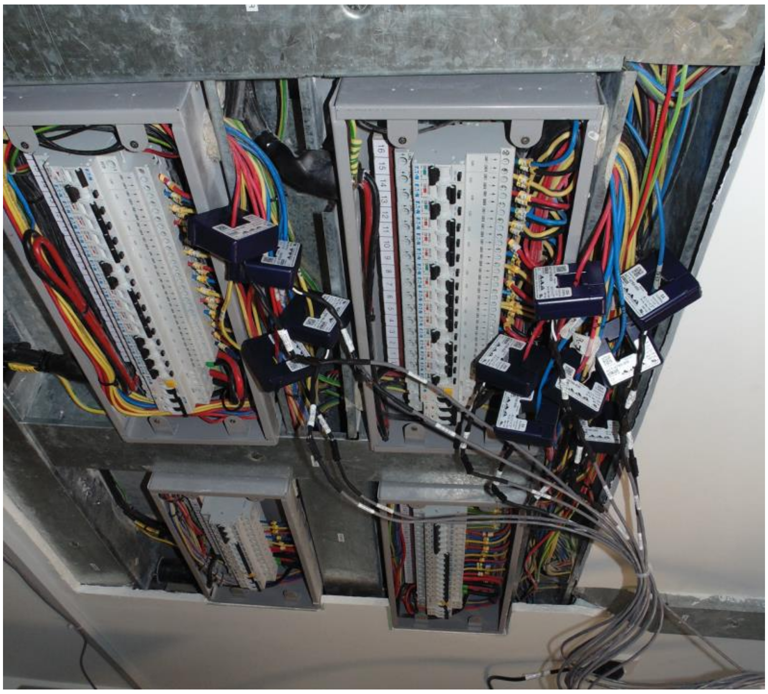
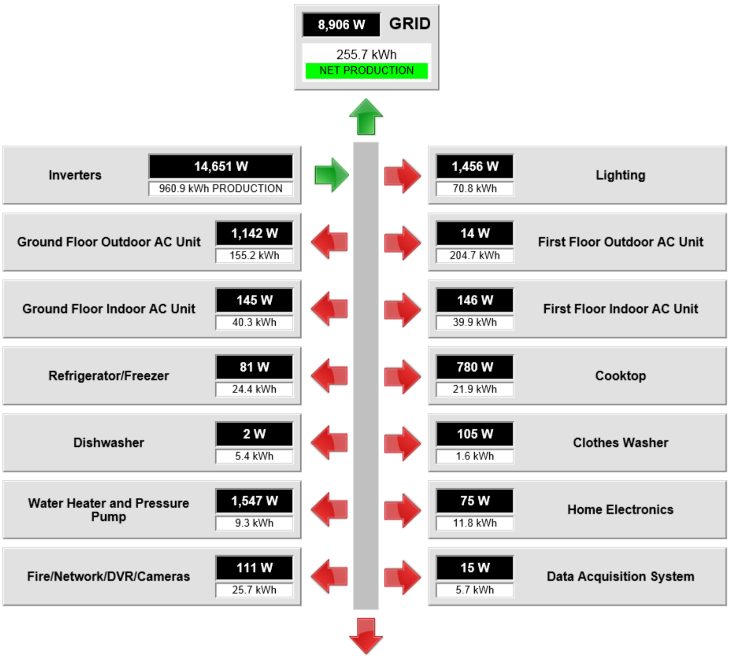


Figure 5.9: Monitoring system principle

The number of data collecting sensors varies according to the room size, layout and the purpose of the measurement (Nicol *et al.*, 2012). Therefore, in thermal comfort surveys, measurements are recommended to be taken at a vertical height of 0.6 m above the floor for a seated person or at the working surface level, but not less than half a metre from any wall (Nicol *et al.*, 2012). Since the internal spaces of the LCB are small, one sensor is used per space located in the centre of the space at 1.2 m above the floor, at least 0.5 m from the wall, and at a distance from any disturbing objects.



(a) Measurement devices connected to the home electricity dashboard



(b) Online direct measurement dashboard

Figure 5.10: Online LCB energy arrangement

The results for a full day were collected from the data acquisition system after monitoring a low carbon reference building for 24 hours (one day) between 8:00 am on the 29th of October and 8:00 on the 30th of October 2014 (Table: 5.5).

Household tasks		Meter reading kWh before test	Meter reading kWh after test	Consumption kWh
HVAC	Ground floor outside AC	95.4	101.2	18.7
	Ground floor inside AC	28.1	31.2	
	First floor outside AC	124.6	131.4	
	First floor inside AC	27	30	
Lights		47.3	50.2	2.9
Water Heater & pressure pump		11.4	12.183	0.783
Cloth washer		1.9	2.8	0.9
Cooking		4.3	6.5	1.2
Refrigeration		5.5	8.2	2.7
Home electronics		8.5	8.912	0.412

Table 5.5: Electricity consumption in kWh/day for the selected household tasks

Furthermore, the energy consumption of the reference LCB was compared to the energy consumption of reference buildings CB1 and CB2 in order to evaluate energy reduction that a low carbon strategy can achieve in the residential building sector (Figure 5.11). Since the total built area and occupancy of these building are not the same, a common measuring unit is required to normalise the values obtained. The suitable common metric unit for this case is kWh/m^2/day/person (from Eq.4.4 reduced for one day). The reference LCB has achieved a substantial reduction in energy use especially for the HVAC system and lighting. This can be referred to the low U value of its fabric, use of LCD lighting and the shading provided.

Summary reference buildings energy usage (kWh)			
Tasks	**CB 1**	**CB 3**	**LCB**
HVAC	67.2	103.35	18.7
Lighting	3.799	20.792	2.9
Hot water	13.2	15.6	0.783
Washing machine	0.214	1.35	0.9
Cooking	4.283	3.78	1.2
Refrigeration	7.452	8.47	2.7
H Elec.	1.011	1.14	0.412
Total daily	97.159	154.482	27.595

Table 5.6: Daily energy consumption of the reference building over the course of one day in October 2014

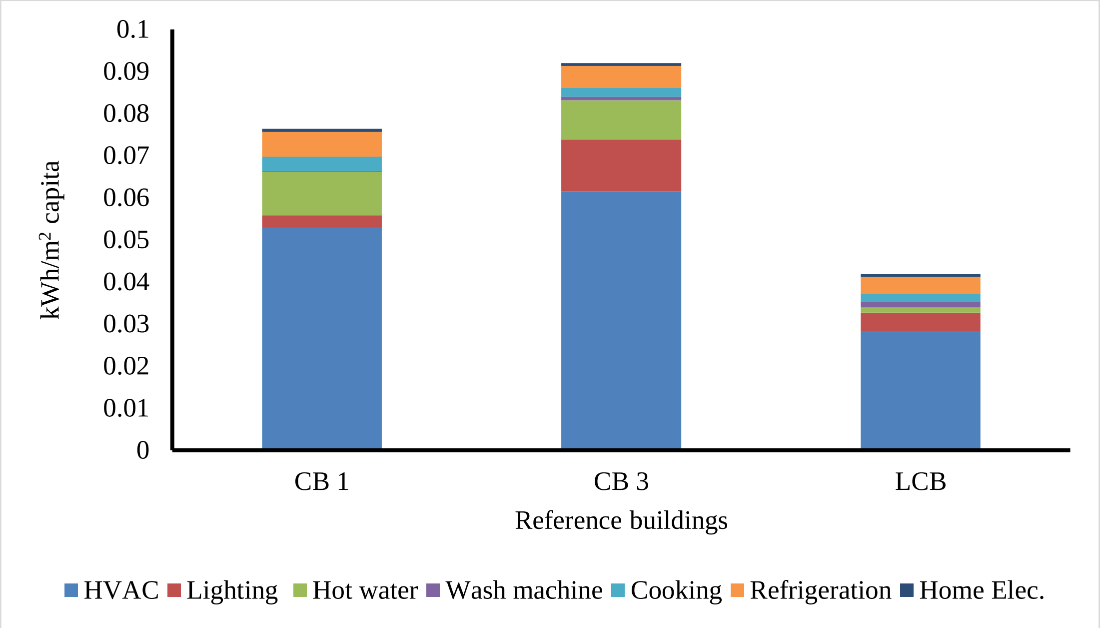


Figure 5.11: One day electricity (the main source of energy) consumption of low carbon and conventional buildings

5.8 Low carbon building design guideline requirements for hot humid climate

The building energy performance guideline is a basic requirement to make decisions for enhancing the energy efficiency strategy that can be used in the future as reference for new building energy analyses and consumption. The LCB design guideline needs to provide an adaptation of different strategies for the entire building to become more efficient and use less energy. Hence, future residential building design in Oman is required to consider the following design aspects: -

1. Design considerations: -
    a. Orientate the building to reduce heat gain from direct sun rays. Also, make use of available cooling breezes. Furthermore, position landscaping and outbuildings to funnel breezes and provide local shading where required;
    b. Provide outdoor living areas for use under mild weather conditions;
    c. Locate pools and spas outside the building if the humidity in the site is relatively low;
    d. Install ceiling fans in all rooms to provide air circulation;
    e. Install rated home appliances.
2. Windows and shading:-

    a. Shade all windows and walls where possible;
    b. Avoid overuse of glazing;
    c. Use low solar heat gain coefficient glazing;
3. Construction systems:-
    a. Use lightweight (low mass) construction (recommended for hot humid weather);
    b. Use light coloured reflective materials for the building exterior;
    c. Design and build for local site conditions;
    d. Insulate internal wall surfaces from any external thermal mass;
    e. Exclude solar radiation from roofs, windows and walls;
    f. Consider shading the whole building;
    g. Select appropriate insulation levels for the climate zone.

5.9 Chapter summary

A vast body of literature, ranging from the background of energy use and indoor environment to the research approaches used in associated studies, has been comprehensively surveyed in this chapter in order to identify the key attributes of low carbon buildings for a hot and humid climate. It analysed the pilot case study houses, where the energy consumption for various home tasks was evaluated. The objective of this case study was to generate effective raw data for pre-processing and analysis purposes. In conclusion, this chapter: -

1. Established the building energy system for evaluating the energy consumption of residential buildings for energy benchmarking;
2. Analysed the building energy sub-system and parameter controlling demands;
3. Reviewed the building energy reduction measures for low carbon strategies in the hot and humid climate;
4. Analysed the building energy profile for the energy diagnostic and strategy application through a case study;
5. Identified the key attributes for the low carbon guideline design for a hot and humid climate.

6 LCB design guideline framework

6.1 Introduction

The previous chapter reviewed energy performance of residential buildings in hot humid climate in terms of low carbon building attributes. The evidence of the performance gap obtained from chapters three and four suggests that the availability of LCB guideline can be translated to a good energy performance of buildings. Therefore, the need exists for low carbon building design guidelines to identify design parameters and their application on future residential buildings. Hence, this chapter specifies the main features of the required LCB guidelines for hot humid climates. The procedures used in this chapter involve direct measurements and modelling to evaluate the values of design parameters in terms of energy measures. The evaluation is used to identify if the energy performance of the case study LCBs meets its design target and how this can be implemented in future residential sector. Further, the use of modelling allows an evaluation of these energy measures and their effect on different aspects of building performance.

This chapter proposes an approach for developing a guideline framework for low energy dwelling. It identifies sensitive and robust design parameters that reduce the energy consumed for different purposes in residential buildings located in climatic regions such as Oman. This approach is made on the development of multi-criteria design guideline framework (MDGF) for the selection of appropriate domestic LCB strategies in Oman (Figure 6.1). In this regard, the research investigates the technical feasibility of the use of low carbon Energy Efficiency Measures (EEMs) implemented in the available low carbon buildings and their performances in the built environment of Oman. The results from this chapter will then be used to develop an innovative integrated design tool.

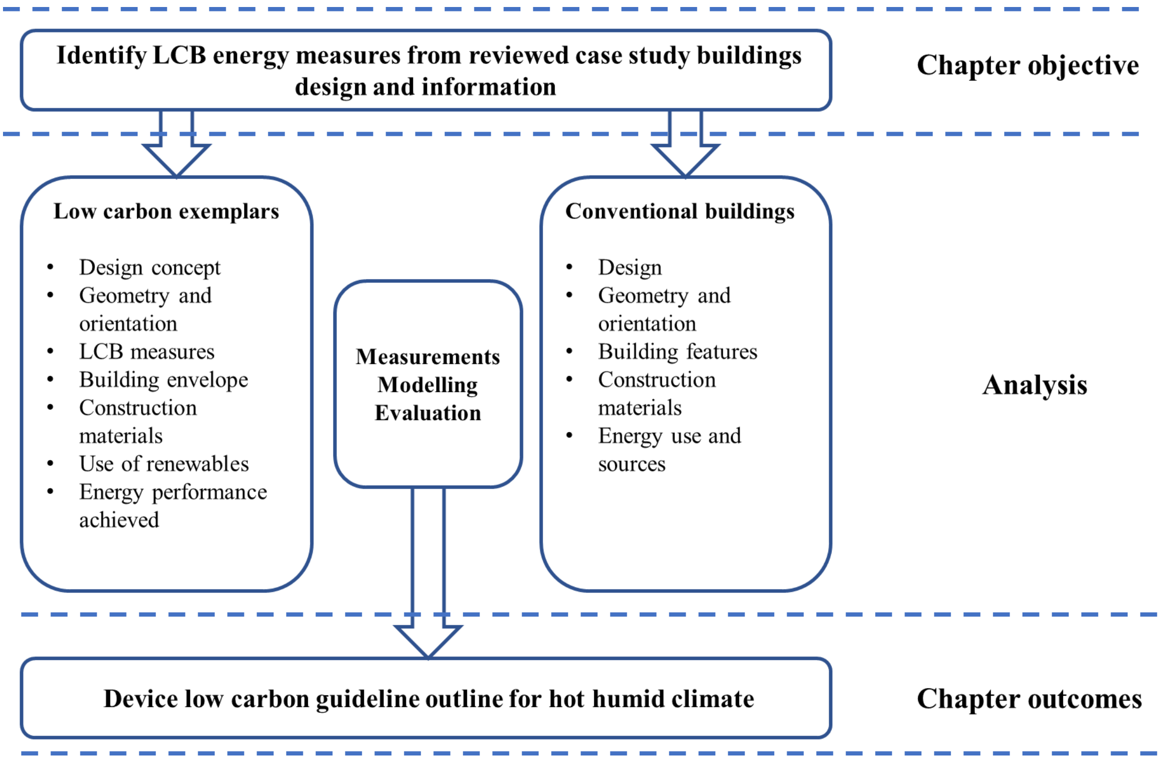


Figure 6.1: Chapter outline and design guideline criteria

6.2 Low carbon building guideline framework and scope

There is a wide range of international design guidance available to improve energy performance of buildings. The Chartered Institute of Building Services Engineers (CIBSE) published Guide (F) for energy efficiency in buildings. Guide F provides information on improving energy performance from the initial design process through the operation, maintenance and refurbishment of buildings (Figure 6.2) (CIBSE, 2012). Furthermore, international codes for sustainability provide guidance on energy conservation designed for specific climatic areas. CIBSE guide F provides energy guidance based on energy measures used in the design and operation stages.

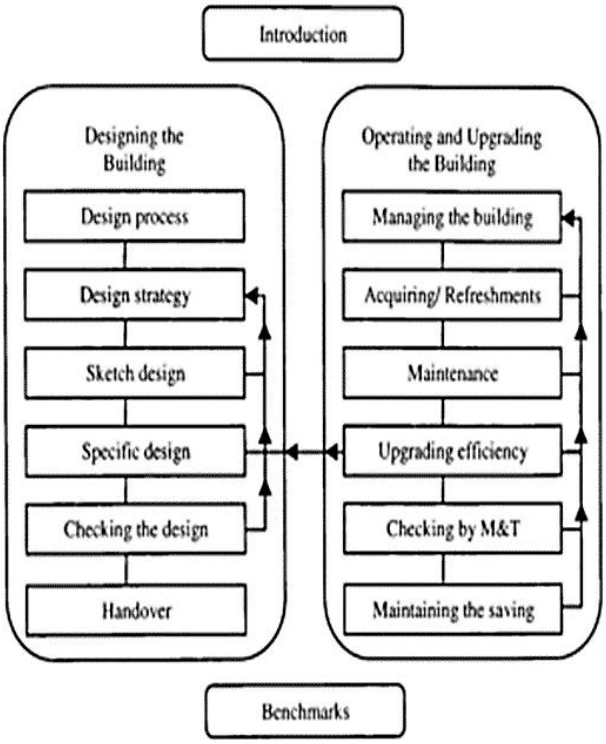


Figure 2.2 Energy efficiency guide F (CIBSE, 2004)

Figure 6.2: Energy efficiency guideline F

(CIBSE, 2004)

Energy measure means specific strategies or technology implemented to reduce the consumption of energy in a building. The design stage pursues a target performance of energy consumption by introducing LCB measures, whereas construction and operation stages involve the physical processes of application of these measures. The building envelope is the main building elements that contribute to the energy performance of buildings; hence, it has been subjected to significant research. Sang, Pan and Kumaraswamy (2014) grouped design measure of building envelope into two main groups namely architectural design measures and material design measures (Table 6.1).

Architectural design measures	Material design measures
Optimise building form to minimize heat gains through surface;	Insulate the exterior wall and roof to avoid humid air infiltration to reduce dehumidification energy;
Orient building towards north-south exposures to take advantage of north–south day-lighting	Use high performance concrete for its thermal mass;
Turn long facades toward the prevailing breezes to enhance natural ventilation	Use reflective exterior wall/roof finishes to reduce solar heat gain;
Employ solar shading devices to block direct solar radiation;	Use innovative construction materials, e.g. Fibber-reinforced polymer;
Use innovative wall type, e.g. double skin wall;	Incorporate windows with low-e or reflective coating;
Proper design of window area and size (window to wall ratio);	Incorporate windows with tinted or multiple layers of glazing;
Install wing walls to improve natural ventilation;	Incorporate windows with thermally improved frame.
Install light shelves to penetrate daylight deep into the building.	

Table 6.1: Building envelope energy measures

(Sang, Pan and Kumaraswamy, 2014)

Aksamija (2013) stated that there are four main consideration for designing high performance building in the hot climate:

Solar control: protection of the building facade from direct solar radiation by self-shading methods (using building form) or introducing shading devices

Reduction of external heat gains: protection from solar heat gain by infiltration using well-insulated opaque envelope elements and from conduction by using shading devices

Cooling: optimise natural ventilation when weather conditions and environmental characteristics of the building permit

Daylight: use of natural light sources while minimizing solar heat gain through use of shading devices and light shelves

The success of LCB energy measures in the operation stage depends on making the right choices during design and their applicability in construction stage. In this regard, the energy efficiency measures (EEMs) implemented in reference LCBs in the climate of Oman will be examined in order to estimate their efficiency in conventional buildings (Table 6.2). Further, the LCB design strategies that are applied in sampler LCBs to reduce base load through evaluation of their design concept will also be examined. Finally, we devise a reference design guideline framework for low carbon building most suited to hot humid climates including orientation, building typology, material properties and design concept (passive/active).

Reference	Energy Measures	Remarks
EEM1	Building shape	Overall building shape i.e. squire rectangular, compactness etc.
EEM2	Building orientation	Long axis and façade direction from north
EEM3	Building materials	Building shell materials and components
EME4	Glazing	Fenestration, windows dimensions and specification
EEM5	Thermal Insulation	External wall insulation
EEM6	Shading	Shading devices within building form or from external objects
EEM7	Natural ventilation	Use of wind breezes
EEM8	Daylight	Utilizing natural lighting
EEM9	Renewables	Uses of renewable energy

Table 6.2: List of energy efficiency measures implemented in reference LCBs

6.3 Architectural specification of the guideline

Buildings are complex products made from many materials and components, which are affected by various design and operating factors. The variation of consumption is impacted by usage behaviour, and the internal conditions and external environment of the building. Many studies have revealed that the design of buildings is composed of two different group of variables: design consideration and design configurations factors (Ibraheem, Farr and Piroozfar, 2017). Design considerations include factors such as the climate, site, topography, neighbouring buildings and available source of renewables. These factors are not under the direct control of designer or may not be subjected to direct modification, whilst design configurations factors are the elements, which can be shaped and modified to fulfil the requirements of the building including building orientation, building geometry, opening size and geometry and their configuration (Ibraheem, Farr and Piroozfar, 2017). Based on this consideration, the proposed architectural design guideline for LCB in the selected environment will include:

- Building Shape, orientation and geometry,
- Building envelope and construction materials,
- Optimising exterior wall insulation to reduce need for cooling,
- Shading to reduce cooling loads and improve thermal comfort,
- Using natural ventilation to reduce HVAC loads and enhance air quality,
- Minimising energy used for artificial lighting, and
- Energy sources and uses of renewables.

6.4 Building Shape and orientation

Building shape and orientation are considered one of the main factors affecting energy conservation in buildings (Abanda and Byers, 2016). Several researches have studied the potential energy conservation affected by building's orientation, shape configuration and compactness (Fallahtafti and Mahdavinejad, 2015). Buildings compactness, or as some researchers call it shape factor, refers to the ratio between the thermal envelope area and building volume (Danielski, Fröling and Joelsson, 2012). Buildings with higher shape factor are less compact and will have larger thermal envelope areas compared to their volume. Hence, the building will be subjected to higher heat gain from solar radiation. In addition, different geometric shapes of building have different solar gains under the same conditions due to its potential direct incident sun ray on its envelope surface. However, the maximum and minimum possible width of residential buildings is limited due to site restrictions and the requirements of natural light and visual comfort. In hot climates, the effect of size on the fenestration on thermal performance of building may be more than the effect of the shape factor (Danielski, Fröling and Joelsson, 2012). A number of studies have evaluated the effects of building shape on energy consumption of buildings in cold climate, but not many are available for hot climate. Ourghi, Al-Anzi and Krarti (2007) analysed the impact of the shape factor on calculation of cooling demand on building in Kuwait and Tunisia comparing rectangular and 'L' shaped buildings and found a strong correlation between the shape factor, the window size and the cooling demand. Further, detailed parametric analysis carried out in Kuwait revealed that the impact of building shape on total building energy demand depends primarily on three factors, the relative compactness (R_C), the window-to-wall ratio (WWR) and glazing type which defined by it solar heat gain coefficient, SHGC. Fallahtafti and Mahdavinejad (2015) studied different shaped building with the same volume based on elementary cubes ordered in different shapes and orientation to obtain the effect of shape and orientation on building energy consumption. From their review, a strong correlation was found between total building energy demand and building size, shape, R_C, WWR, and SHGC. However, building geometry's varies, which is not covered within the content of this research. Therefore, the analysis of geometry and orientation of building on energy consumption in this research will be limited on the covered case study buildings (Table 6.3) (Appendices C &D).

Ref. Convectional Building	Shape	Shape factor	WWR	Ref. LCBs	Shape	Shape factor	WWR
CB1	Square	0.96	18.2%	(LCB1)	Rectangular	0.82	23.9%
CB2	Square	0.85	22.3%	(LCB2)	Cylindrical	0.61	18.8%
CB3	Rectangular	0.97	21.5%	(LCB3)	Rectangular	0.7	17.6%
CB4	Square	0.84	25.0%	(LCB4)	Square	0.54	18.6%
CB5	Square	0.95	19.3%	(LCB5)	Rectangular	0.61	16.5%

Table 6.3: Reference buildings shapes properties

6.5 Building envelope and construction materials

The building envelope and construction materials have strong effects on a building's annual energy and occupants comfort more than any other elements (Aksamija, 2013). The building envelope is required to fulfil its function by supporting its own weight, allowing daylight to interior spaces, blocking unwanted solar heat gain, protecting occupants from outside environment, providing views to the outside and blocking unwanted air and water penetration (Ibraheem, Farr and Piroozfar, 2017; Aksamija., 2013). Since building envelope is one of the main factors that influences a building's energy performance, it was an area of materials innovation and design improvements and modification to improve its thermal performance (Figure 6.3) (Technology Roadmap: Energy Efficient Building Envelopes, 2017). The energy consumption of buildings associated with envelope components is highly variable based on building type, climate zone and conditions, construction practice, occupants' behaviours and building age. Whereas it has been found that in United States, a residential buildings roof is responsible for 14% of heating and cooling loads, similar data from Europe stated an average of around 32%. Similarly, the impact of windows on heating and cooling energy is 31% in the

United States and 15% in Europe (Transition to Sustainable Buildings Strategies and Opportunities to 2050, 2013).

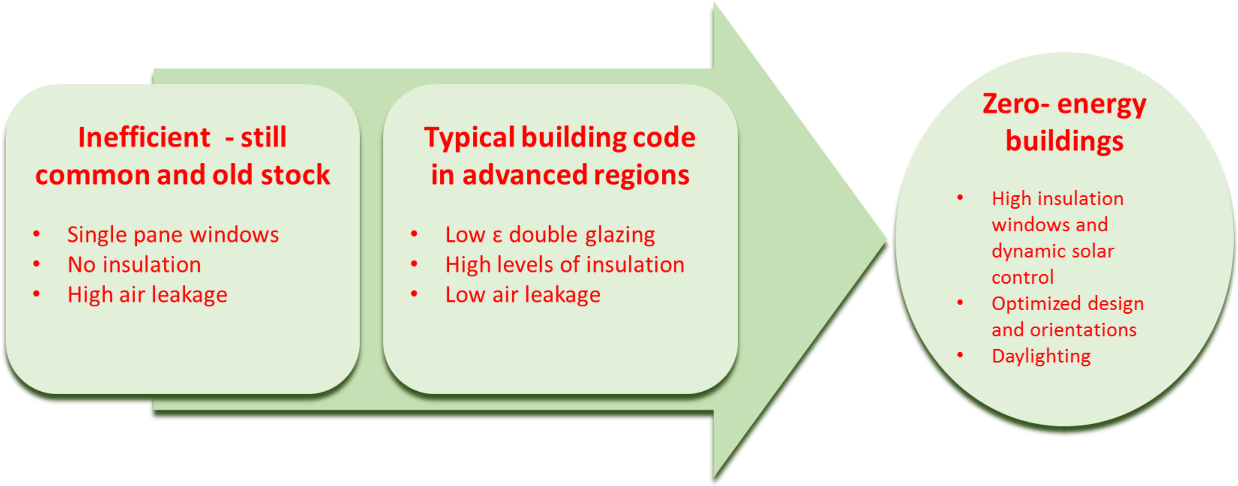


Figure 6.3: Progress of development of LCB envelope

(Resource: Technology Roadmap: Energy Efficient Building Envelopes, 2013)

6.5.1 Building envelope

The envelope of building consists of opaque areas and fenestration includes windows that are separating internal environment from external environment. Whole Building Design Guide (WBDG) (2017), stated that building envelope is the enclosed area surrounding the internal of the building consists of the foundation, walls, doors, windows, roof, and any elements included in the shell of the building. ASHRAE (2007) 90.1, provides periodically updated recommendations for building envelopes based on climatic zones, within which the building envelope is divided into four major systems:

- **Below grade system:** element separates building environment from the ground,
- **Wall system:** the vertical opaque parts of the envelope e of the building.
- **Roof system**: refers to the overheads opaque elements separates buildings' environment from the external.
- **Fenestration system:** include all glazed area windows, louvers and entrances.

Building envelopes are often constructed from various layers of materials with relative thicknesses arranged to yield better thermal insulation based on the use of the building and whether conditions (Bojić and Loveday, 1997). Wall, roof and fenestrations are more subjected to heat gains. Therefore, they have been targets for material improvements since the early twentieth century due to material innovation (Arnold, 2017)**.** These elements of the envelope will be considered in this research to identify energy-efficient design measures through a detailed review of these systems in both groups of the referenced buildings.

6.5.2 External walls design and materials

Walls, for thermal envelope evaluation of building comprises of four main elements include exterior texture and colour, structural elements, insulation and interior finishes. Guidelines for Condition Assessment of the Building Envelope (Standard ASCE/SEI 30-14) provide guidance for assessing performance of building envelope systems and materials. The standard classified building envelope into four groups namely mass walls, metal building walls, steel-framed walls, wood-framed and other walls (Structural Engineering Institute. and American Society of Civil Engineers., 2014). The envelope of single family residential buildings in Oman are made of 220 mm thick precast concrete blocks and a reinforced concrete frame structure. The exterior wall finishes including 10 - 20 mm sand cement plaster coated by paint and texture. In the reviewed case study the LCBs and conventional building shows huge difference in building fabric, which subsequently reflected in deference in energy consumption of buildings (Table 6.4) (Energy Balance, 2015). Building materials properties were collected from the reference documents submitted to TRC, although windows U values for LCB3 seems to be higher than expected value for double glazing window while it looks too low for triple glazing in LCB4. However, these values will be used in this research at this stage, but these values will be considered for modification if required at the modelling stage to expected values.

Hence, the need exists to improve the building fabric, and provide performance measures such as insulation or cavity wall. Insulation is one of the widespread effective energy measures adopted, and can be implemented within the building fabric, for an example in the external walls and roof of a building. Furthermore, a wide range of materials can be applied with in the building envelope acts as thermal insulation.

Envelope elements	CB1 to 5	LCB1	LCB2	LCB3	LCB4	LCB5
Wall Description	Single leave concrete block with internal external sand cement plaster	Reinforced concrete, concrete blocks and local recyclable concrete base materials	Malty-layers of 20 mm plaster, 210 mm compressed earth blocks, 200 mm vapour barrier, 20 mm pumice light weight concrete blocks, 190 mm cement plaster	Nudura concrete block 8" & external / internal plasterboar d	2 layers of Autoclaved aerated concrete (ACC) with air cavity	Two leaves of concrete blocks 90 mm outside and 190 mm inside with 50 mm expanded polystyrene
Thickness	240 mm	450 mm	640 mm	318 mm	480 mm	340 mm
U Value	2.02	0.67	0.0133	0.233	0.46	0527
Roof Description	150 mm reinforced concrete slab, 40 mm white cement tiles	Layers of 2.8 mm roof covering, 1 mm waterproof, 18 mm plywood, 100 mm polysocennarate insulation and 150 mm concrete	150 reinforced concrete slab, 15 mm BASF master-seal water proofing, 200 mm PE foil, 50 mm sand, 40 mm white cement tiles	200 mm hollow concrete slab with 50 mm tile cover	240 mm Hollow-brick ribbed concrete slab covered with 40 mm tiles and 100 sand for mm vegetation	Concrete slab covered by sand cement screed, EP insulation, waterproof and tile
Thickness	190 – 200 mm	271 mm	455 mm	250 mm	380 mm	350 mm
U Value	2.66	0.17	0.0171	0.339	0.35	0.348
Windows Description	Single layer simi-laminated glass layer thickness 4 to 10 mm	Stained Glass, single - 10 mm thick and Stained glass, triple glass, with a 6mm thick air cavity	2 layers separated with argon gas used REHAU-GENEO	Double glazing with shading coefficient of 0.448	Triple Glazed layers with argon gas field	Double glazing
Thickness	4 – 10 mm	60 mm	72 mm	60 mm	280 mm	35 mm
U Value	4	2.35	1.1	3.25	0.16	2.1

Table 6.4: Summary of reference buildings fabric

6.5.3 Low carbon building roof options for hot climate

Traditional concrete roofs absorb maximum heat gain, which is a major source of discomfort for air-conditioned buildings. Traditional roofs in the context of this research refer to the uninsulated concrete roofs, which are widely used in Oman, and their thermal performances are relatively low when compared to LCB roofs. Low carbon roof options are those where thermal properties reduce heat gain more than regular roofs. In this context, low carbon roofs for hot humid climate may include green roof, insulated roof and shaded roof.

Solar gains from a roof is normally larger than the other building elements in countries where most of the year the sun is perpendicular to horizontal surfaces. However, since solar energy is abundant and clean it will be essential to have solar systems in the roof of building to benefits from it by shading the building and producing renewable energy. There are two main types of solar technologies that are applied to buildings at present; these include solar thermal and PV.

6.5.4 Construction materials and market support

A review on construction materials and elements used in exemplar LCBs case study shows the use of materials, which are not available in the local market (Table 6.5). The review of buildings materials focused on the envelope materials because of their effects on thermal properties of envelope and subsequently energy consumption. Lack of availability of materials in the local market is one of the factors for the increase of the total cost of the building. Further, introducing new materials in the construction industry of building reduces the ability of small contractors to submit tenders for these types of building. It is important that the construction consultant and contractor are familiar with the specification of construction materials in order to construct the building for the function for which it has been designed.

Materials or elements	**Ref. Building**	**Source**
Concrete & reinforced concrete	All	Oman
Concrete blocks	All	Oman
Hollow concrete	LCB3, 4	Oman
Roof tiles	All	Oman
NUDURA concrete	LCB3	Canada
AAC concrete	LCB4	Oman
Light Wight concrete blocks	LCB2	Oman
Compressed earth blocks (manufactured for this building)	LCB2	Oman
Plaster boards	LCB3	Oman
BASF master-seal water proofing	LCB2	Oman
Expanded polystyrene	LCB 1,2,5	Oman
PE foil	LCB2	Oman
Vapour barrier	LCB2	Oman
Polysocennarate (Polyisocyanurate)	LCB2	UAE
18 mm plywood	LCB1	Oman
Single layer Simi-laminated glass	Conventional buildings	Oman
Stained Glass REHAU-GENEO	LCB2	UK
2 layers separated with argon gas	LCB2	UK
Double glazing	LCB3, 5	Oman
Triple Glazing windows	LCB4	Turkey

Table 6.5: Summary of LCBs materials sources

The consequence and significance of materials cost and availability has been reflected on the total cost of low carbon reference buildings (Table 6.6). The total building cost includes all hard and soft costs to construct and make the building ready to function according to its design purpose. Total building costs includes design cost, initial construction costs, materials cost, consultant fees and life services cost. Materials cost will contribute to the initial cost, but their thermal performance will influence life services cost (Table 6.6). Hence, project breakdown shows the significant rise in the cost of the building due to the materials and technologies used. Therefore, an optimal cost benefit required to balance between initial cost of materials and cost benefits from life service.

Construction elements	**Cost in OR (£)**				
	LCB1	**LCB2**	**LCB3**	**LCB4**	**LCB5**
Earth work	3725	6270	5985	4435	5565
Labour cost	15300	16000	11000	10000	17000
Materials	65200	73200	81000	46000	67000
Doors	8500	8900	8600	7800	10200
Windows	5300	5600	6500	4800	8100
PV system	7650	18940	17550	210680	16080
Solar hot water heater	875	875	875	875	875
Electrical system	1790	1810	1210	2500	3300
Pluming	2210	2570	2355	2450	3200
Sanitary system	2150	2250	2200	2200	2650
Finishing	6550	7000	6500	6100	7500
Appliance	5700	6400	6200	6700	8410
Cost per m^2	386 (772)	584 (1168)	450 (900)	325 (650)	448 (896)
Total Cost	125,000 (250,000)	150,000 (300,000)	130,000 (260,000)	115,000 (230,000)	155,000 (310,000)

Table 6.6: LCBs exemplar cost breakdown in OR and (£)

6.6 Thermal insulation requirements within building envelope

Thermal insulation in building envelopes are an important factor to reduce energy consumption of building associated with cooling and heating by reducing heat gain and loss. The thermal performance of construction elements depends on its materials, thickness, and the properties of insulation used (Nematchoua *et al.*, 2015). Thermal conductivity of insulation affected by factors including its density, porosity, moisture content, and temperature difference between inside and outside of the building (Abdou, 2005). Therefore, it is necessary to select the right insulation materials for the weather conditions and obtain the optimum thickness of insulation. Many studies on thermal insulation of buildings have revealed variations of insulation materials selection, performance, applications, and cost, and payback periods due to energy saving (Hasan, 1999; Abdou, 2005; Ozel and Pihtili, 2007; Aïssani *et al.*, 2014; Nematchoua *et al.*, 2015). Further, studies conducted on the implementation of thermal insulation in the hot weather show the possibility of reducing energy demand of building due to applying insulation can be up to 35% (Table 6.7).

Research topic	**Researcher**	**Year**	**Reduction**
Energy productivity evaluation of large scale building energy efficiency programs for Oman	Krarti & Dubey	2017	25%
Evaluation of large scale building energy efficiency retrofit program in Kuwait	Krarti	2015	15%
Optimal design of residential building envelope systems in the Kingdom of Saudi Arabia	Alaidroos & Krarti	2015	35%

Table 6.7: Energy reduction due to implementing thermal insulation in hot climate

6.7 Shading devices

Large windows and highly glazed envelopes have been increasingly used in the construction of new residential buildings in Oman, which requires careful design consideration (Figure 6.4; Figure 6.5). Glazed areas in buildings allow more access to daylight, and provide a pleasant external view. This design concept needs more attention since windows used in construction of buildings in Oman are made of single glass layer of 2 or 5 mm, which increases sunrays passing through non-shaded windows and glazed facades, and consequently increases solar gain and the need for air-conditioning in summer.

Figure 6.4: Large unshaded windows in a building in Muscat

Figure 6.5: Shading device misplaced

Shading devices play a significant role in reducing the heat gain of the building and providing a comfortable indoor environment (Alzoubi and Al-Zoubi, 2010). The use of photovoltaic (PV) cells generate electricity from the sun rays and, as a shading devices for windows achieves the double benefits of providing sheading and clean energy (McKeag, 2014). Furthermore, combining external solar shading devices either traditional or more recent transparent see-through and photovoltaic panels, has the potential of adding architectural features when combined with photovoltaic panels (Ibraheem, Farr and Piroozfar, 2017).

Freewan (2014) examined the performance of three different type of shading devices in Jordan and proved that all shading devices helped to improve the thermal and visual environment of the building at the time of the experiments (Figure 6.6). His research revealed that the major influence of shading on solar gains and thermal performance of building.

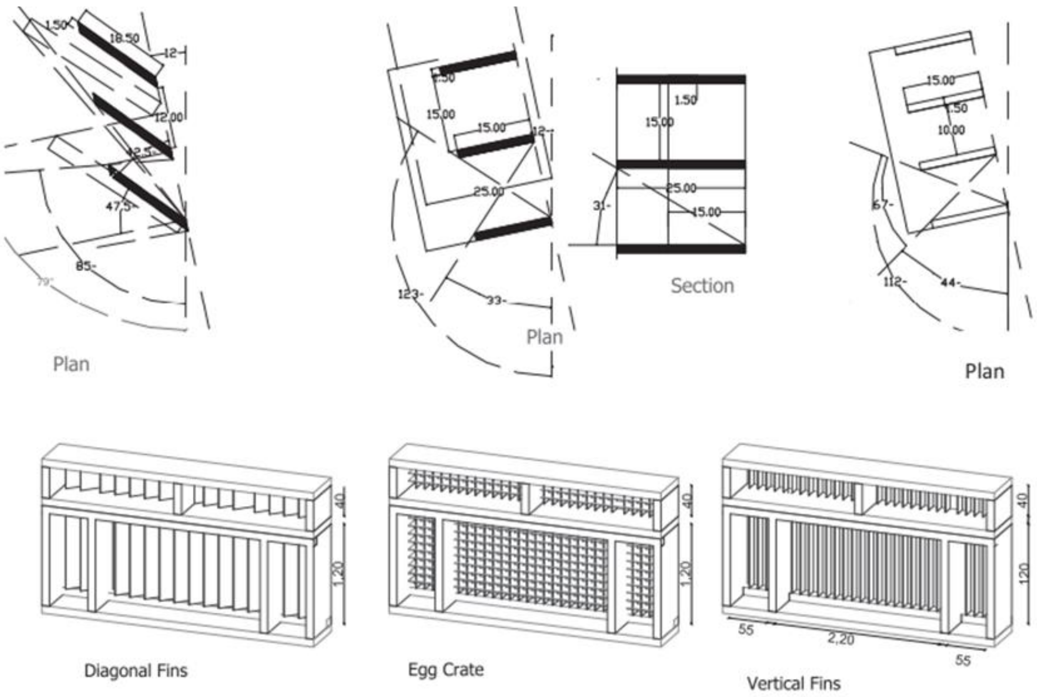


Fig. 2. Shading devices installed in the tested offices.

Figure 6.6: Shading devices examined by (Freewan, 2014)

A review of exemplars of Omani low carbon building also shows that they have provided more adequate shading devices compared to conventional buildings (Figure 6.7). Hence, design guidelines should include the use of shading devices integrated properly within the building envelope, especially in the east, west and south sides of the building.

Figure 6.7: Use of shading in reference LCB1& LCB3

6.8 Ventilation

Ventilation is the replacement of internal air by fresh air withdrawn from external sources to maintain a comfortable indoor air quality (Khan, Su and Riffat, 2008). Natural air ventilation has the potential to improve the thermal comfort for cooling purposes without consuming a significant amount of energy (Schulze and Eicker, 2013). However, it is important to consider wind direction, temperature and humidity as these factors will have strong impact on the potential use of natural ventilation. Referring to the available state of the art of low carbon, in Oman only one building designed to maximise use of potential natural ventilation exists. Bustan Oman green building, located in Nizwa University, was constructed with a system that directed wind to the building courtyard passing over the green roof then through a water pond to reduce its temperature, then the ventilation system air is drawn into the building by fans passing through pipes in the pond (Figure 6.8); (Figure 6.9) (University of Nizwa, 2015). The test of this system on 14 October 2014 at 1:30 am sought to reduce air temperature by 6.4 °C, which might be sufficient to reduce internal building temperature to an acceptable level for the occupants, which might discourage them from turning on the air-conditioning devices that consume more energy (Figure 6.10).

Figure 6.8: LCB4 water pond and pipe system

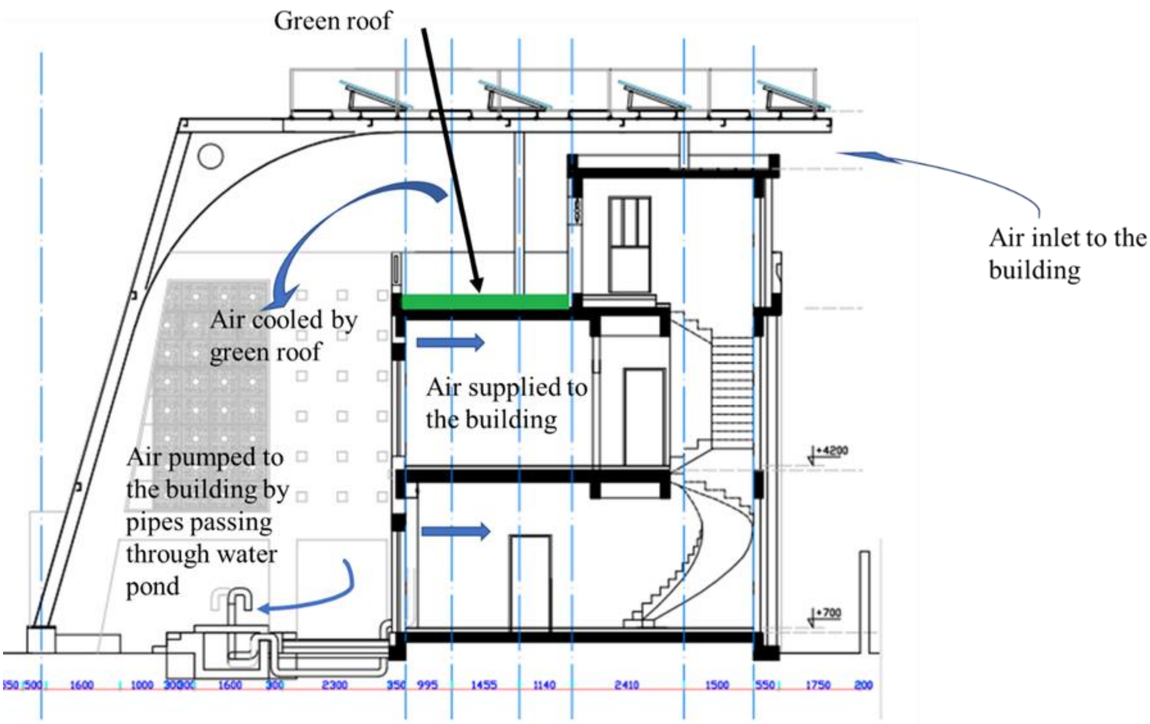


Figure 6.9: LCB4 natural ventilation system

Figure 6.10: Recording temperature reduction due to natural ventilation

6.9 Daylight use and availability

A successful optimisation of daylight in building requires considerations within design aspects such as light distribution, glare and solar gains based on the façade elements layout (Altomonte, 2009). Daylight design also needs to consider the annual dynamic usage of spaces to provide design that meet availability and needs (Acosta *et al.*, 2015). There are several methods adopted to quantify daylight allowed through windows. Daylight factor is one of the simplest and most commonly used method to quantify daylight. It measures the potential illuminance inside a room in the worst possible scenario, under overcast sky conditions when there is less exterior daylight (Acosta *et al.*, 2015). The method adopted by Ghisi and Tinker (2004), called the Ideal Window Area IWA, was used to predict the potential of energy saving due to daylight. The concept of IWA was based on a balance between solar thermal load and daylight supply.

Acosta *et al.* (2015) suggested that square windows produce daylight factors higher than those of horizontal rectangular windows do, and are noticeably higher than that obtained by vertical windows in the opening surfaces. In the studied LCBs exemplars, it has been observed that daylight utilized without potential increasing of solar gain (Figure 6.11).

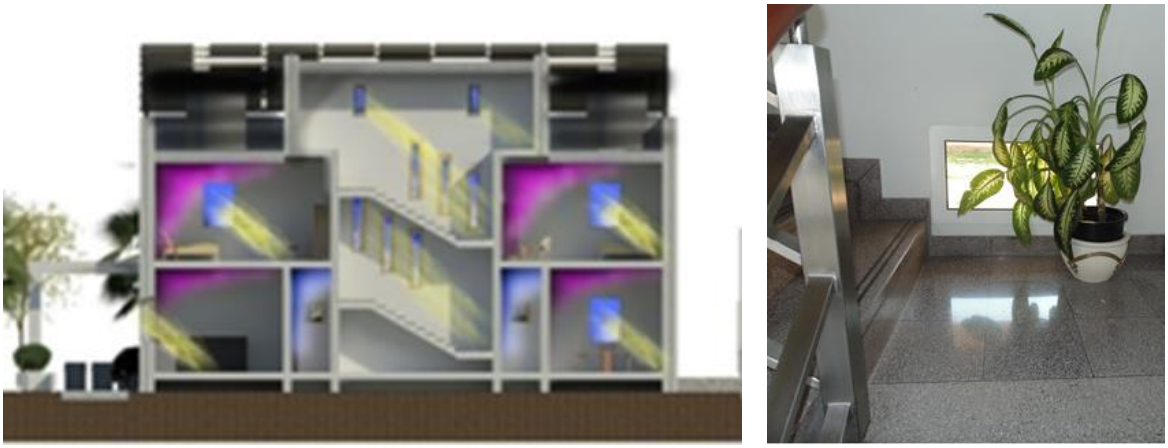


Figure 6.11: Section with photo illustrates utilization of natural lighting in LCB3

6.10 Energy uses and sources

Buildings receive their energy needs from conventional and non-conventional energy sources. Conventional source refers to non-renewable sources of energy, which include fossil fuels including oil, natural gas, and coal. In contrast, non-conventional energy sources refer to resources such as biomass, geothermal, wind and solar. In Oman, the residential building sector relies heavily on conventional energy sources in the form of electricity generated from burning oil or gas, gas for cooking, and liquefied petroleum gas (LPG). Nowadays, the use of gas for cooking in Omani dwelling is very limited due to the widespread availability of electric ovens and stove. In contrast, the use of renewable energy in residential building is almost non-existent for the reasons described in chapter four. At present, only five LCBs have examined the use of renewable energy in residential building in the form of PV panels and solar hot water. Certainly, these buildings have proved that the use of solar energy in residential building is a promising technology that is able to reduce energy demand from conventional sources. Furthermore, the PV systems in three out of the five buildings observed in these studies were able to produce more than their annual energy need.

6.10.1 Use of renewable energy

The potential utilisation of renewable energy sources depends on availability and the possibility of utilisation. In Oman, the most promising renewable energy sources in residential building are wind and solar (Al Busaidi *et al.*, 2016). However, as previously noted, solar is the only renewable resource used in buildings. Hence, the focus in this section of the research will be focused on solar energy.

Typically, the total annual solar energy at the earth surface is 1×10^{18} kWh, which is equivalent to 13×10^{12} tons of standard coal, and is also equivalent to 1000 times the world proven oil reserves, and is also more than ten thousand times the world's total annual energy consumption (Yang, He and Ye, 2014). The GCC countries are located in a region with a high abundance of solar radiation of up to 6 kWh/m^2/day, with 80-90% clear skies throughout the year (Munawwar and Ghedira, 2014). The Authority for Electricity Regulation in Oman, argues, "*Oman has solar energy potential to provide sufficient electricity meets all of Oman's domestic electricity demand"* (Study on Renewable Energy Resources, Oman, 2008). However, humidity, dust, limited rainfall and the absence of technical guidance is considered the main obstacles for utilising solar energy in Oman. A site visit to the LCB3 references building confirmed that heavy dust accumulated on the surface of the solar water heater after two weeks of cleaning, confirming that the solar heater was positioned in a place where dust can accumulate faster (Figure 6.12). Additionally, the fact that the Majan Electricity Company's main office PV panels were removed due to wind effects confirms there is an absence of technical guidance in the use of solar panels (Figure 6.13).

Figure 6.12: Dust accumulation effects on solar hot water heater

Figure 6.13: Wind effects lead to the removal of PV system

Nevertheless, the results from one month energy monitoring of the LCBs shows that PV panels and solar hot water heater were able to provide large share of buildings energy demand (Table

6.8). Harvesting solar energy in residential buildings in Oman will assist in the solving the country's future demand of energy and will tend to reduce CO_2 emissions rather than be contributing to this problem.

Month	LCB1		LCB2		LCB3		LCB4	
	G	C	G	C	G	C	G	C
Jan	328.09	397.82	1608.36	1508.36	1922.04	1229.43	1831.82	1135.73
Feb	406.15	490.09	2311.03	2211.03	2379.36	1498.16	2267.67	1405.95
Mar	916.36	1283.19	4620.58	4720.58	5368.36	3354.55	5116.36	3172.14
Apr	1222.34	1544.88	6557.81	6757.81	7160.88	4287.88	6824.74	4231.34
May	1320.13	1760.47	6772.63	6972.63	7733.79	4744.53	6370.75	3949.87
Jun	1188.79	1105.22	5931.83	5991.83	6964.36	4192.40	7637.44	4735.21
Jul	863.60	920.82	5798.03	5698.03	7402.59	4049.91	6055.10	3754.16
Aug	861.76	918.65	6186.22	6086.22	6806.00	3669.34	6486.51	4021.64
Sep	938.36	1109.20	4995.86	5995.86	5497.25	3230.30	5239.20	3248.31
Oct	621.86	835.07	3094.80	3394.80	3643.07	2240.74	3472.05	2152.67
Nov	379.59	648.69	1792.56	1892.56	2223.74	1306.71	2119.35	1314.00
Dec	268.29	417.13	1293.34	1393.34	1571.72	923.57	1497.94	928.72

Table 6.8: RE in (kWh) generation (G) and energy consumption (C) of LCBs

6.11 Evaluation of energy measures

Two typical Omani dwellings CB1 and CB3 selected for the analysis in order to assess energy reduction measures for residential building in Oman. Besides, LB3 the analysis confirmed low carbon building for comparison from the results from CB1 and CB2. The selection of these buildings was made based on accuracy of energy audit results compared to the remaining conventional buildings, size of buildings close to the size of reference LCB, location and availability of required modelling data. Whilst reference LCB was selected because of its high performance, compared to other reference LCB, one year energy consumption of CB1 and CB3 were obtained from local utility companies in order to provide measured reference data for validating of simulation results. In contrast, energy consumption of reference LCB3 was obtained from measurements provided by TRC.

This research focused on energy consumption of buildings, hence the IES Virtual Environment (IESVE) used to perform whole-building energy simulation analysis. IES is a powerful, in-depth suite of building performance analysis, which allows the design and operation of buildings to be tested using different options, which identify best passive solutions, compares low-carbon and renewable technologies, and draw conclusions on energy use and CO_2 emissions and occupant comfort. The calculations of energy consumption in the program were based on a real weather data that can be used for any period from a day to a year. In addition, IES includes Macro Flow simulation to evaluate naturally ventilated and mixed-mode buildings. Building envelope components and properties such as walls, roof, floor, windows and other architectural elements for the three buildings are listed for modelling and analysis (Table 6.9). Further, heat gain from occupants, lightings, and equipment usage profiles established were based on energy audit and data provided by TRC (Table 6.9, Table 6.10, Table 6.11 and Table 6.12).

Parameters		**Reference low carbon building (LCB3)**	**Reference conventional building (CB1)**	**Reference conventional building (CB3)**
External walls	Materials	Nudura concrete	Concrete	Concrete
	Thickness	318 mm	240 mm	240 mm
	U Value	0.233	2.02	2.02
Internal walls	Materials	Concrete & plaster	Concrete	Concrete
	Thickness	280 mm	240 mm	240 mm
	U Value	0.82	2.02	2.02
Floor	Materials	Hollow concrete	Reinforced concrete	Reinforced concrete
	Thickness	250 mm	200 mm	190 mm
	U Value	0.339	2.66	2.80
Roof	Materials	Shaded hollow concrete	Reinforced concrete	Reinforced concrete
	Thickness	250 mm	200 mm	190 mm
	U Value	0.339	2.66	2.80
glazing	North	27%	18%	27%
	West	22%	21%	25%
	South	12%	32%	30%
	East	0%	24%	27%
Doors	Materials	Wood	Wood	Wood
	Thickness	200 mm	50 mm	50 mm
	U Value	0.23	0.46	0.46

Table 6.9: Modelling parameters of reference building

Internal heat gains in the case study were collected from people, lighting, home electronics and equipment (computers, Television and miscellaneous), and cooking. The sensible gains for people were set to 75 W/person in accordance with the ASHRAE handbook fundamentals (2013) linked to occupancy profiles of each space based on the energy audit (see Table 6.10).

No.	Spaces	No of people	Usage profile week days in hours	Usage profile weekends & holidays in hours	Lighting W/m²	Equipment W/m²
1	Setting room	4	6 h	6 h	6	14
2	Dining room	4	2 h	2 h	5.5	8
3	Master bedroom	2	4 h	4 h	4	8
4	Bedroom 1	1	4 h	4 h	4	6
5	Bedroom 2	1	4 h	4 h	4	6
6	Kitchen	4	3 h	3 h	13	18
7	M-Bedroom bathroom	2	1 h	1 h	6	2
8	Toilet 1	2	1 h	1 h	6	2
9	toilet 2	4	1 h	1 h	6	2
10	Corridor	4	1.5 h	1.5 h	6	0
11	roof room	2	0.5 h	0.5 h	6	0
12	Staircase	4	0.5 h	0.5 h	6	0

Table 6.10: Internal heat gain profile data for LCB3

No.	Spaces	No of people	Usage profile week days in hours	Usage profile weekends & holidays in hours	Lighting W/m²	Equipment W/m²
1	Setting room	7	6 h	10 h	6	14
2	Dining room	7	3 h	3 h	6	8
3	Master bedroom	2	1 h	1 h	6	8
4	Bedroom 1	8	1 h	11 h	8	6
5	Bedroom 2	8	1 h	11 h	8	6
6	Bedroom 3	8	1 h	11 h	8	6
6	Kitchen	4	3 h	4 h	10	18
8	M-Bedroom bathroom	2	1 h	2 h	6	8
9	Toilet 1	2	1 h	1 h	6	4
10	toilet 2	3	1 h	1 h	6	4
11	Corridor	7	0.5 h	0.5 h	7	0
12	roof room	3	0.5 h	0.5 h	8	0
13	Staircase	7	0.5	0.5 h	8	0

Table 6.11: Internal heat gain profile data for CB1

No.	Spaces	No of people	Usage profile week days in hours	Usage profile weekends & holidays in hours	Lighting W/m^2	Equipment W/m^2
1	Setting room	5	6 h	11 h	6	14
2	Dining room	5	3 h	4 h	6	8
3	Master bedroom	2	7 h	9 h	8	8
4	Bedroom 1	2	8 h	10 h	6	6
5	Bedroom 2	2	8 h	10 h	6	6
6	Kitchen	3	3 h	4 h	18	18
7	MB bathroom	2	1 h	1.5 h	6	6
8	Toilet 1	2	1 h	1.5 h	6	4
9	toilet 2	2	1 h	1.5 h	6	4
10	Corridor	5	1 h	1 h	6	0
11	roof room	2	1 h	1 h	4	0
12	Staircase	5	1 h	1 h	4	0

Table 6.12: Internal heat gain profile data for CB3

Openings for windows, external and internal doors were modelled in great detail because their area represents the air flow plugged into IES VE as a percentage of the opening area. In additions, thermal bridging, a factor referred to as "Ψ value" and measured in (W/m^2k) was applied to the overall U-value of each element. The application of this factor was to account for heat loss through thermal bridging per m^2 of each element area and linked directly to the external environment. Internal gains from equipment and cooking were assumed as an average based on the ASHRAE handbook (2013). The appliances were linked to occupancy profiles of each space within the building in order to provide an estimation average value of consumption. However, not all appliances are linked to occupancy profiles, such as refrigerators, which are continuously on. Hence, due to the lack of complete equipment usage data, overall consumption pattern assumptions were inevitable. Simulation took place several times with alterations in assumptions to correlate with measured data (Table 6.13).

Input parameter	LCB3		CB1		CB3	
	Base values	**Altered values**	**Base values**	**Altered values**	**Base values**	**Altered values**
External walls overall U value	0.233	0.260	2.02	2.40	2.02	2.40
Internal walls overall U value	0.82	0.260	2.02	2.40	2.02	2.40
Floor U value	0.339	0.255	2.02	2.40	2.02	2.40
Roof U-value	0.339	0.274	2.02	2.20	2.02	2.40
Building area	287 m^2	250 m^2	212 m^2	210 m^2	240 m2	265 m^2
Glazing U value	3.25	2.05	4	2.8	4	2.4
Occupancy	4	4	7	7	5	7
Infiltration rate	Constant airflow 1ach	Constant airflow 1ach	MacroFlo profiles	Constant airflow 1ach	MacroFlo profiles	Constant airflow 1ach
Overall glazing ratio	17.6 %	25%	26.%	24%	28.5%	30 %
Internal gains from appliances and lighting	52.8 W/m^2	60 W/m^2	52.8 W/m^2	60 W/m^2	52.8 W/m^2	60 W/m^2
Internal gains from cooking	12 W/m^2	20 W/m^2	12 W/m^2	60 W/m^2	12 W/m^2	60 W/m^2

Table 6.13: Summary of calibration of modelling input parameters

Parameters values used and results obtained from this stage represent as usual scenario (Figure 6.14) (Figure 6.15). Then whole buildings simulation analysis utilized to model existing CB1 and CB3 houses with different energy measures applications. These measures described in previous sections of this chapter includes orientation, shading devices, combined and interactive effects of both wall insulation and roof insulation. Finally, energy profiles for each scenario used to obtain percentage energy reduction due to the applications of each measure and to estimate the potential annual energy saving based on the application of these measures in conventional buildings (Figure 6.16), (Figure 6.17).

The initial model validation was carried out to cross reference the simulation inputs towards actual data. In this case, the model has been calibrated taking into accounts the main features of the buildings, their orientations, materials properties and usage profile. The main features reserved unaffected in the modelling were building layout, rooms arrangements and WWR. Buildings orientations have not been justified as these considered one of the major factors of buildings' energy consumption, hence changing orientation may lied to unrealistic consumption. Though, the usage profile of the building considered as constants for both period weekdays and holidays included weekends, however daily human uses of energy at homes are not the same. The building simulation models assume that there are a number of fixed metabolic heat generators, which passively experience the indoor environment. Such models ignore the fact that buildings users are not passive and static. In fact, occupants influence their buildings spaces environment by operating the artificial lighting systems, the window blinds and glare protection devices and/or the air-conditioning systems etc. Hence, modelling is based on assumed standard use behaviours, despite highly variable energy use practices due to the variations in metabolic heat gain, receptacle load and light load in different hours.

Because the tendency of heating and cooling energy consumption is affected by thermal performance of the building envelope (U value), it is necessary to consider a more realistic values for these parameters. Since some of building U values obtained from the official documentation of these buildings have shown either lower or higher values (table 6.4), therefore it worth to consider modifying these values if necessary to their common values. Thus, U-values for LCB3 windows are modified to 2.05.

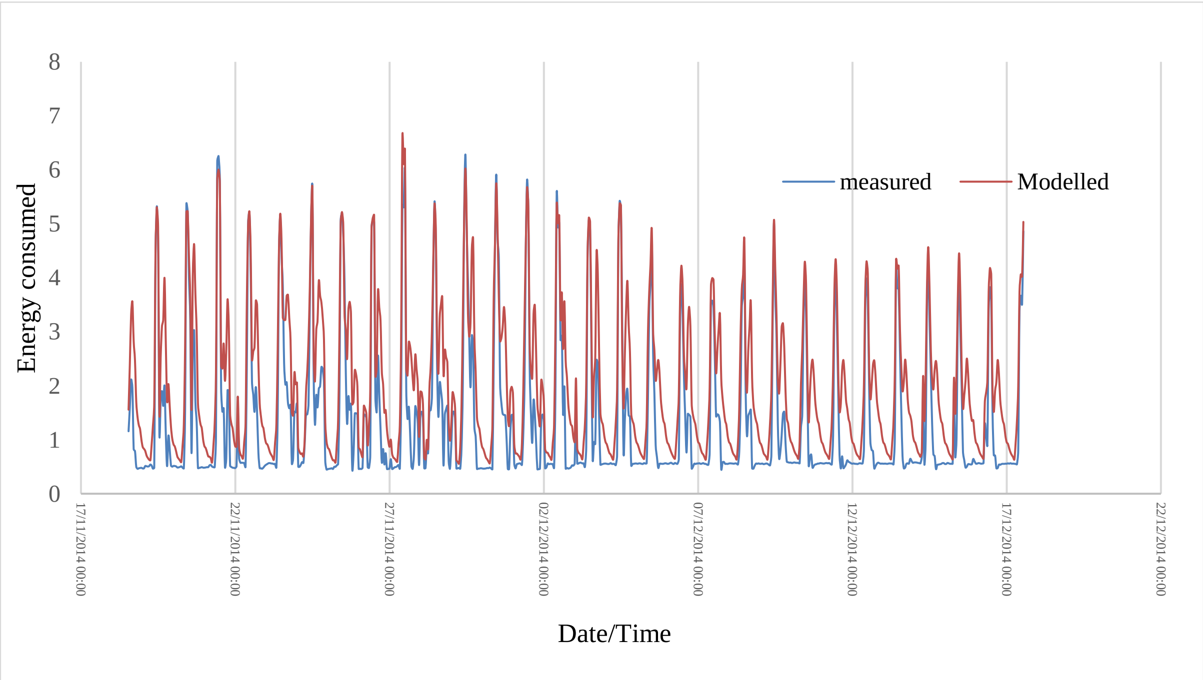


Figure 6.14: One month modelled vs. measured energy consumption of LCB3

Measured energy consumption of LCB3 available for the period from 18/11/204 13:00 to 17/12/2014 13:00, hence, modelled energy consumption carried out for the same period. Whilst, energy consumption of CB1 and CB2 are available for one year based on monthly records, hence the modelled energy profile needed to match annual energy consumption. In terms of residential building energy usage, it was not possible to get modelled values equal to measured values since human activity differs from day to day, especially in holiday periods. The noted disagreement between simulated and measured results in the initial simulation demonstrates the need for changes to the model parameters were identified. In this regard, further justifications were made in order to obtain modelled energy consumption close to the measured values (Figure 6.16). These assumptions include:-

- Ignoring shading from the surrounding homes;
- Assuming the air flow is constant at 1 ach when occupied;
- Assuming windows and door are closed;
- Assuming home occupied full year.

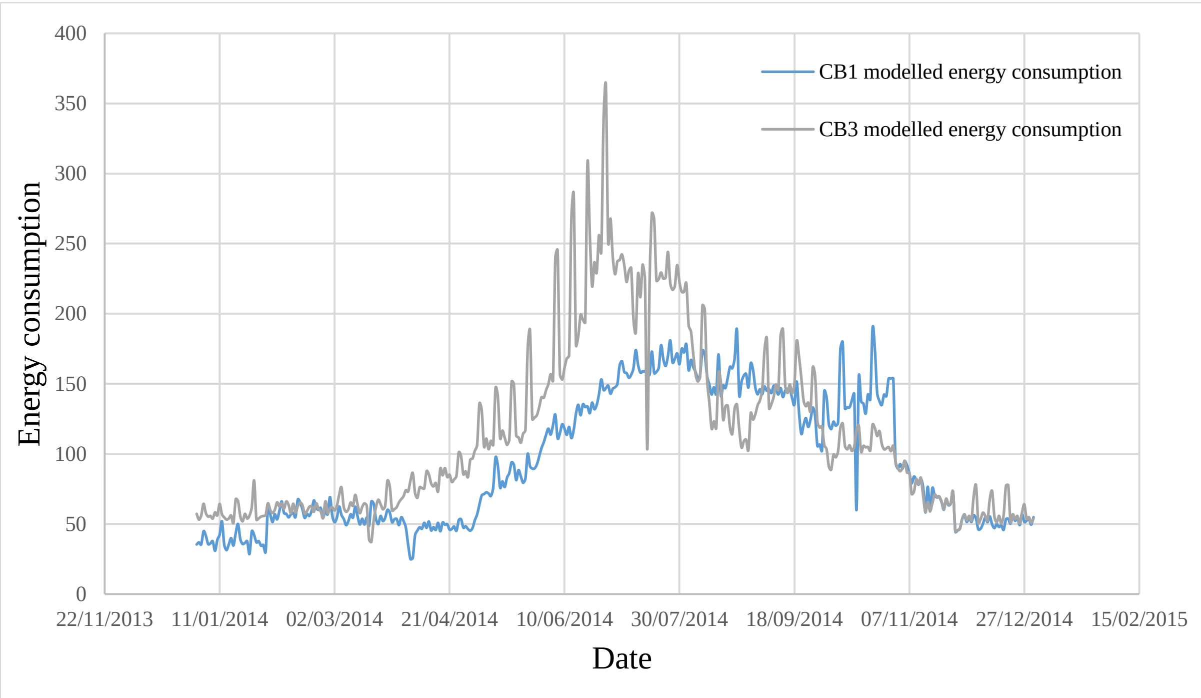


Figure 6.15: Modelled annual energy consumption of CB1 and CB2

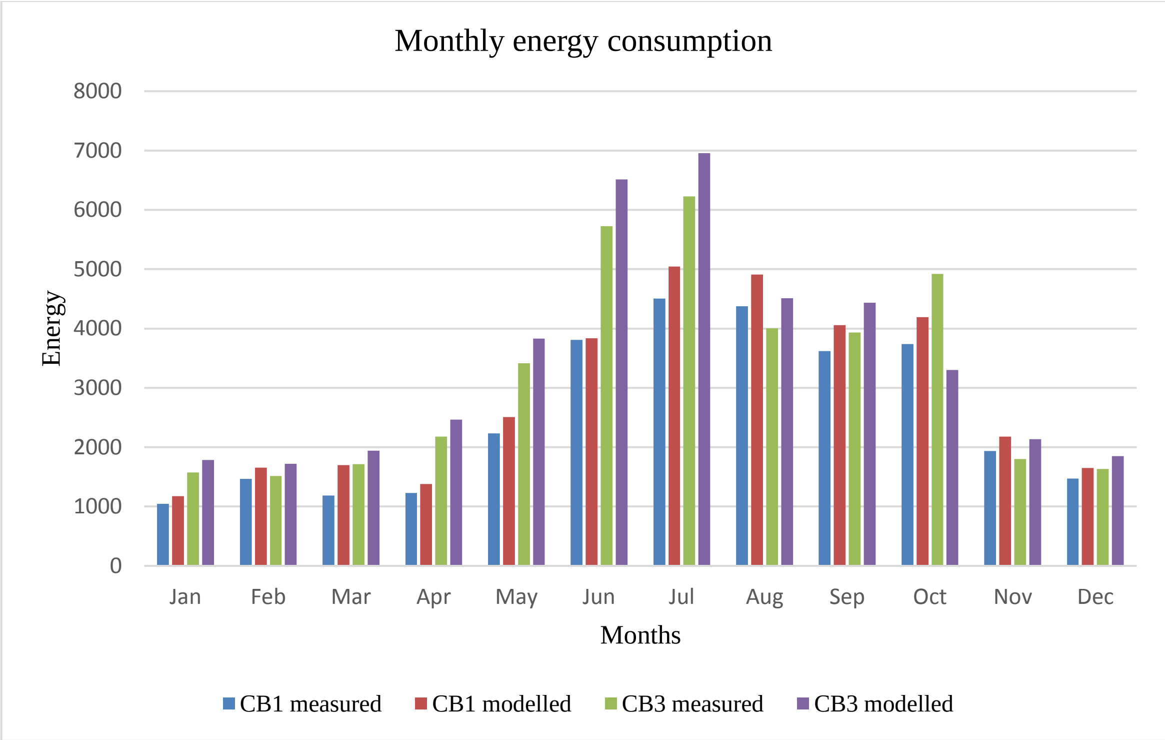


Figure 6.16: Modelled vs measured monthly energy consumption for LCB1 and LCB3

The next stage of the modelling process involved an attempt to simulate the annual energy consumption of CB1 and CB3 using the IES, where in each stage deferent energy measures are implemented in order to obtain percentage reduction of energy consumption caused by these implementation (Figure 6.17). Consequently, a parametric modelling was performed and the simulated energy results were compared to those measured through the relationship of energy consumption (kWh) per floor area unit in m^2. The results of the model will be further analysed for cost benefits in the next chapter.

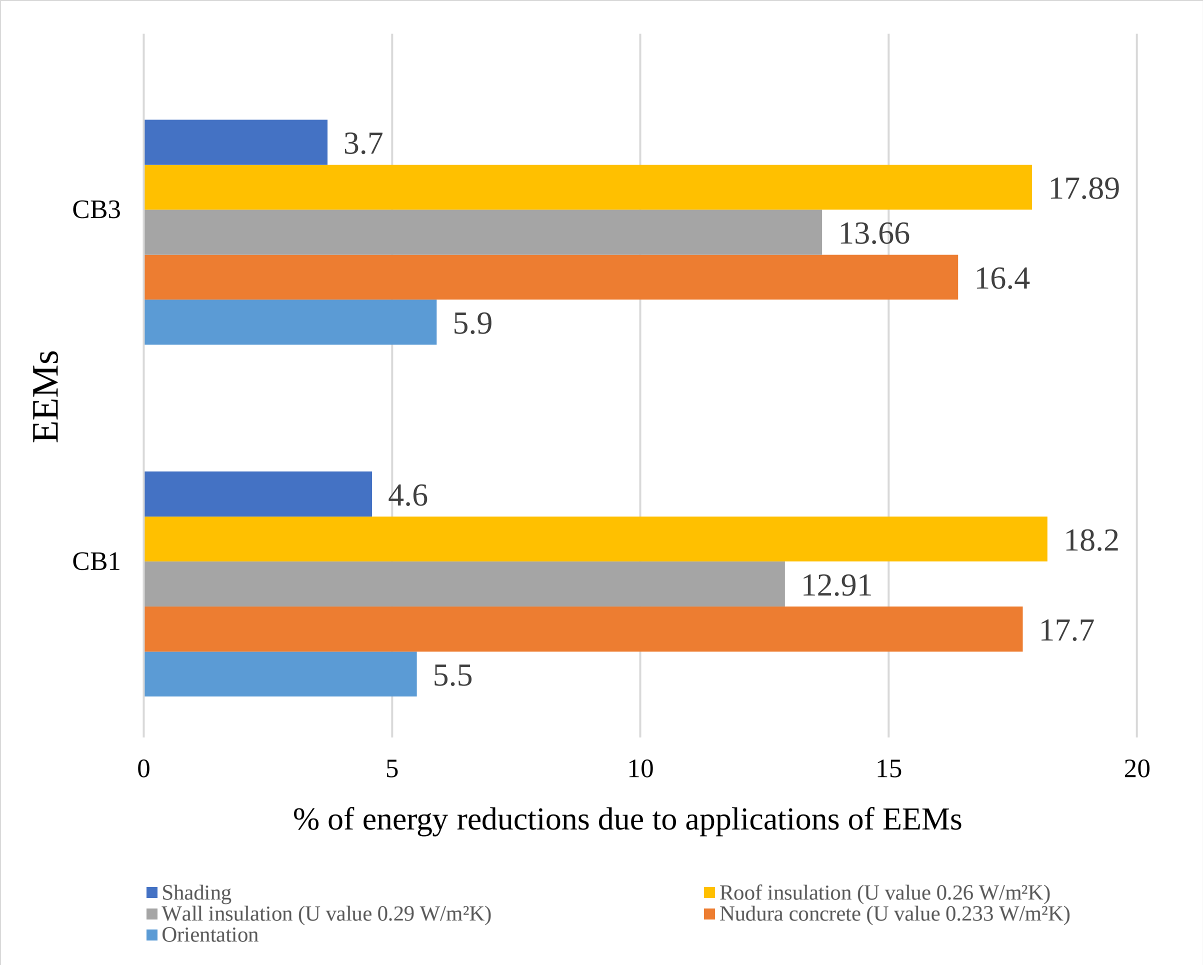


Figure 6.17: Summary of percentage energy reduction due to implementation of EEMs

The results from the simulation revealed that implementation of these energy measures can lead to reduction ranging from 3.7% to 18.2% of the usage of non-renewable energy (figure 7.1). However, the application of more than one EEMs would results into more energy reductions. This suggests the need to implement these measures in the future construction of residential building in Oman through as recommended in the design guidelines for LCB. Furthermore, a simplified energy template to estimate energy demand of building based on these results will be needed in order to help designers and engineers in the selection of the optimal design option.

6.12 Proposed LCB guideline framework and energy template

The simulation results show that simple strategies can be effectively implemented to reduce domestic buildings energy demand. Thus, the energy performance of buildings should be improved in the early stages of design. The implementations of building orientation, shading devices, insulation low U values building materials and glazing can substantially benefit the energy performance of a building. This can be improved further by implementing renewable energy sources within the design. Therefore, the construction industry should be encouraged to implement such strategies in future and existing buildings. Hence, this research suggests recommendations related to the key energy efficiency indicators to be considered as guideline for energy efficient residential buildings in the hot humid climate (Table 6.16).

	Elements	**Recommendation**
Architectural	Optimise building	Reduce building surface to volume ratio R_c in order to minimizes areas exposed to sun compared to the size of the building
	Orientation	Orientate building to the north to make use of the northern façade to provide natural lighting, larger windows can be installed in this façade while minimizing areas of windows in the southern façade
	Site	Understand environmental conditions of the site to capture winds breezes in the moderate temperature seasons
	Shading	Combine shading devices with in the building envelope, and make use of the available shading objects
	Wall type	Integrates multi-layer external walls in order to improve building fabric U value
	Window	Use WWR, area and shape that are able to provide required ventilations and daylight without increasing overall U value of the building shell
	Additional structures	Merge wind catchers structure within the design to provide natural ventilation
	Renewables	Integrate PV panels and solar hot water heater with in the roof of the building in a safe and functioning manner
Material	Insulation	Insulate the exterior wall and roof to avoid high heat gains and to reduce required energy for thermal comfort
	Building fabric	Use high performance concrete for its thermal mass;
	Texture	Use reflective exterior wall/roof finishes to reduce solar heat gain;
	Construction	Use innovative construction materials that are environmental friendly
	windows reflectivity	Incorporate windows with low-e or reflective coating
	Windows type	Incorporate windows with tinted or multiple layers of glazing;
	Windows frame.	Incorporate windows with thermally improved frame.

Table 6.14: Framework of energy efficient building guideline

Generally, these recommendations represent a system of criteria characterizing the efficiency of passive house by using relevant literature and experts' methods. However, in order to implements energy efficient criteria in the residential building sector, an integrated analysis and rational decision-making tool at the micro and macro levels will be needed. In addition, economic and legal/regulatory decisions, and other aspects of political, social, culture, ethical, psychological, educational, environmental, provision, technological, technical, organizational and managerial consideration will need to be considered and further investigated. For simplicity, the application of such criterial guides to estimate the successes of these criteria in the operation stage of the building from the design stage, and an energy-efficiency calculator template will be needed. The next chapter will focus on establishing an energy-calculator model for the hot humid climate of Oman and similar environments.

6.13 Chapter summary

This chapter proposed a low carbon design framework for energy efficient domestic buildings in the Sultanate of Oman, which has a hot humid climate. Energy reduction measures for residential building were reviewed and examined in order to determine their optimal application. The design strategies and techniques involving these energy reduction measures have been investigated and approved through multi rounds of simulation. Then, a proposed framework was developed which incorporates factors concerning architectural design strategies, building envelope design, and on-site renewable energy strategies considering Oman social economic factors.

The analysis has shown potential energy consumption reduction in domestic building by 67% based on considering these measures. Consequently, the results suggested that it is important to establish a residential building energy template (energy calculator) to act as tool for developers, architects and civil engineers to design low energy homes in Oman that meet local requirements needs and overcomes environmental challenges. Hence, the following chapter will focus on designing energy template for homes in Oman and similar environments based on an 'energy consumption definition system' (in kWh/m^2). The energy template principle will be based on the framework established in this chapter and the finding presented in chapters 2, 3, 4 and 5.

7 Chapter VII: Low carbon building template

7.1 Introduction

Designing buildings for high levels of energy performance is a complex task because buildings energy usage is difficult and involves multi-factors. Hence, evaluation of building energy conservation is even a more complicated. In general, performance evaluations are mostly applied for large and complex buildings, such as office buildings, seeking certifications. Whilst, for small projects, i.e. single family buildings, the design team often do not include an energy performance professional. Hence, the architect makes design decisions according to individual views and knowledge (Yildiz *et al.,* 2012). In this regard, architects may have general knowledge about effects of building form, materials, and required HVAC systems for building related to its energy performance. Therefore, if the impacts of these factors on the energy consumption of building are measured for the architects, then this measurable factor can be translated to an improvement of building energy performance from the early stages of design (Schlueter and Thesseling, 2009). Therefore, this research suggests that *"the early design process of residential buildings should involve additional professionals on energy performance design aides supported by simulation tools, in order to assists energy performance of building at the early design stages"*. One method to achieve this task is to provide information to architects using paper-based documents in the form of framework guidelines, national codes and standards (Aksamija, 2015), such as the one provided in chapter six of this thesis. Furthermore, the availability of an energy efficiency tool or calculator that is designed based on the conditions of the building site will help the designer of the building to estimate and compare energy consumptions of deferent options.

This chapter, therefore, aims to develop a building energy model for residential buildings reflecting the variation in energy consumption caused due to application or non-application of EEMs. It describes the devising of a design tool called Residential Building Energy Efficiency Template (R-BEET) that aims to estimate monthly and annual building energy consumptions and its performances in hot-humid climates. In this regard, this chapter demonstrates how the proposed template can be used and applied within the context of Oman. This tool considered the first of its kind designed especially for Oman.

The tool has been developed in Excel workbook format, and it includes separate input sheets for each variable that affects home energy and the end user. The selection of Excel for formatting this template was due to its ease of use and possibility of use by all building stockholder including less educated occupants. It presents a detailed design for the new performance analysis package, using the equations listed in chapter five as a set of functional requirements. The design takes into account the methods that will be used to represent physical systems within the template; home tasks energy system will be used, thermal envelope of the building, and then generates a performance report accordingly. The chapter concludes with an overview of the design decisions and compromises that are possible to be presented by this template.

7.2 Low carbon building template outline

Building energy models have been widely used in measuring energy performance in buildings (Ingle et al., 2014). It allows the analysis of energy-efficient technologies to determine the most effective design of the building in order to select a suitable option (Hong *et al.*, 2000). In this study, the design parameters including EEMs investigated in chapters five and six were assumed to be the most important factors affecting annual energy consumptions in residential buildings. Other parameters were considered to be less significant. Based on this approach, fifteen parameters categorised into three groups were identified as the most important for the formulation of R-BEET (Table 7.1).

Social	**Economical**	**Environmental**
Lifestyle	Cost of construction	Climate conditions
No. of occupants	Cost of energy	Type of fuel
Home appliances intensity	Construction materials	Building orientation
	Size and location of windows	Use of renewables
	Size of building	Adoption of daylighting
	Age of the building	
	Home appliances quality	

Table 7.1: EEMs and parameters of R-BEET

This is an energy calculator tool that quantifies building energy consumption and hence, provide a graphical compression of energy performances of a proposed building compared to a baseline. The energy consumption of the proposed building is calculated based on its design criteria, home equipment, electronics devices, usage profile and occupancy, whilst baseline energy refers to the energy requirements. The tool has been developed in Excel workbook format including 14 sheets (Figure 7.1). The first sheet is named ‘home’ and gives an introduction to the R-BEET’ goal and requirements. The second sheet is the start page, which includes general data on the building under evaluation i.e. building area, plot area, location, owner, and internal spaces. The next 8 sheets of R-BEET consist of user input data sheets involving data on envelope, HVAC, hot water (HW), lighting, home appliances, home electronics, renewable (RE) and occupancy profile. In addition, they contain a separate sheet for generated energy performance report. Further, they contain a user manual for general information and instruction on how to use this tool. Finally, two sheets for calculation and referencing data such as a weather file and home appliances energy consumption list.

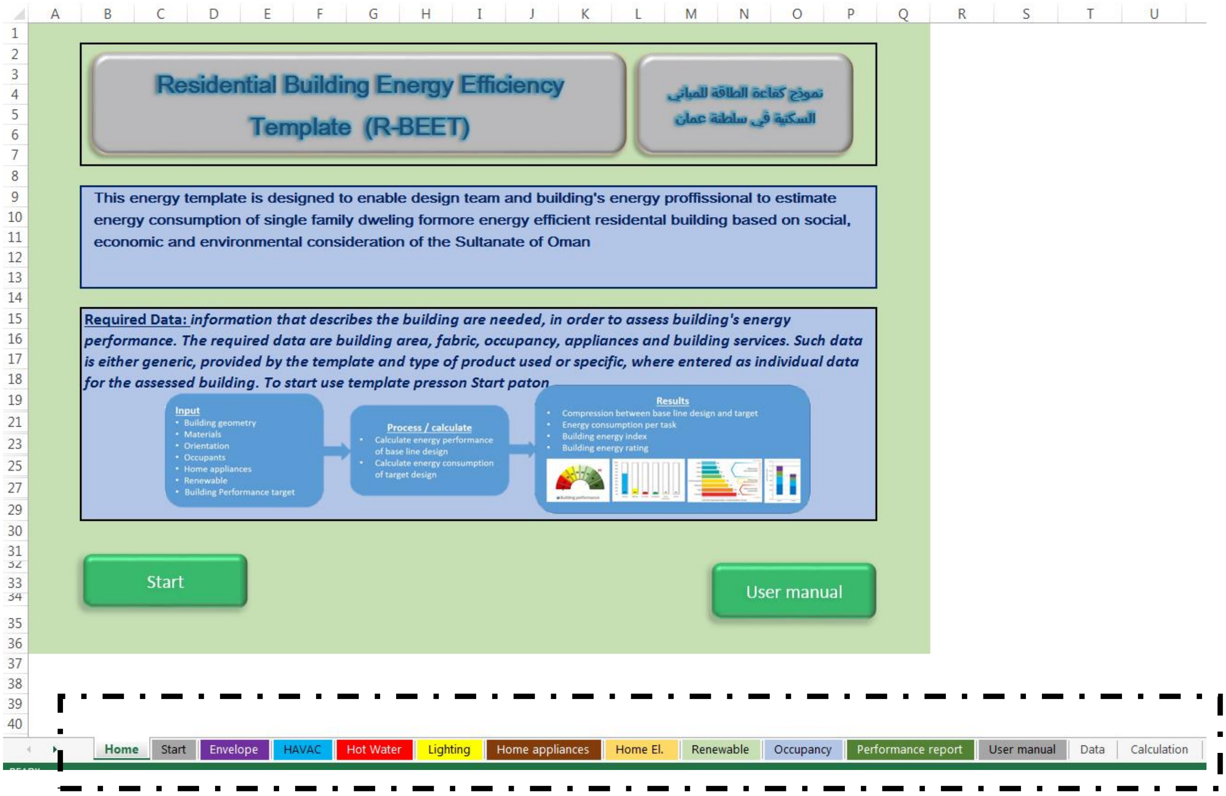


Figure 7.1: R-BEET home interface and Excel sheets

For simplicity in using the tool these sheets, tabs were hidden and the navigation forward and backward between sheets has been provided by navigation tab located within the data entry areas.

7.3 Theoretical framework

Common methodologies used in building energy rating have been adopted within the framework of R-BEET. The calculations of energy performances were made based on formulas generated in chapter five, while building performance report generated based on the results obtained from building energy consumption (BEC) and required energy consumption (REC) explained in chapters five and six. In order to compare building performance within a common context, two scenarios are considered in the performance report. It can be applied to a new building for comparing different design options or existing building for improving energy performance (Figure 7.2). In addition, it can be easily used for implementing a national energy policy.

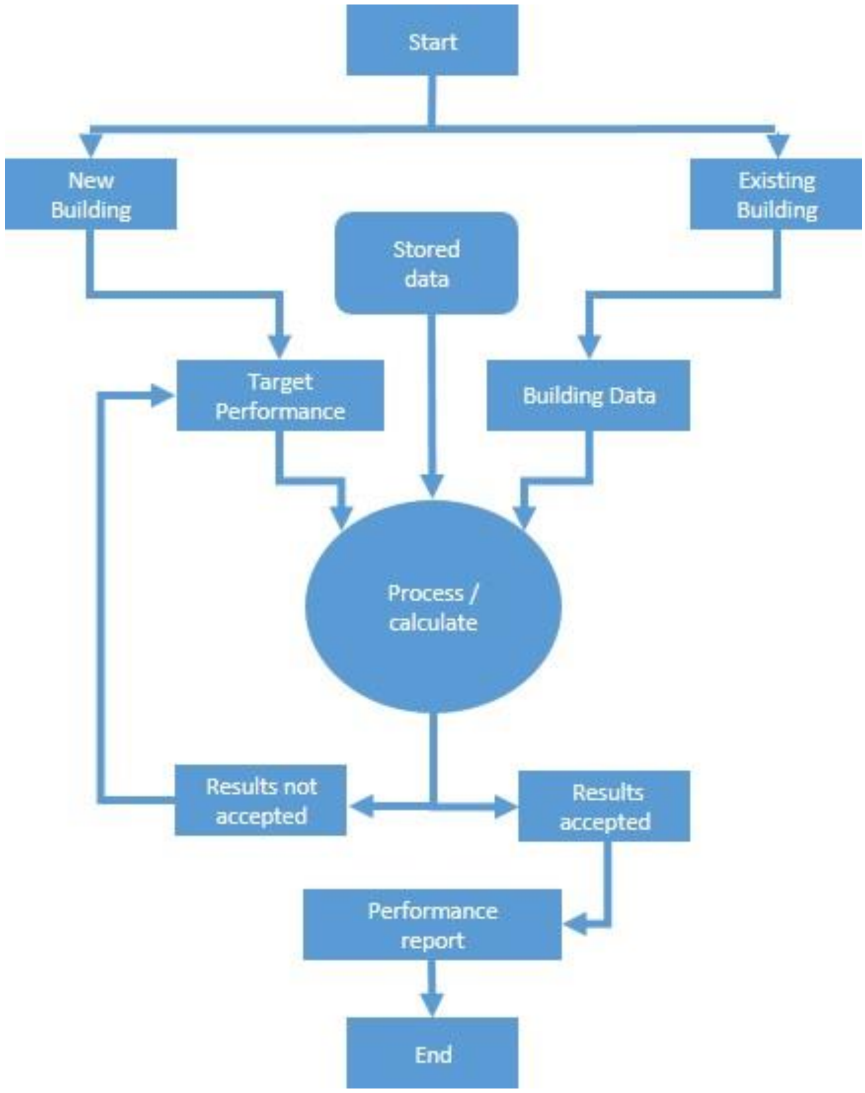


Figure 7.2: Schematic diagram of R-BEET principle

The alternate Reactive Energy Management Model REMM seeks to offer energy performance of a building as reflected in real life situations, which not only help control energy uses but also shows where energy is consumed the most. However, this model (R-BEET) is more versatile and useful as it computes the monthly energy requirements and consumption. It starts by entering the building descriptions through user interfaces based on criteria including materials, building geometry, type of construction, usage, energy expended in form of building services such as Air-Conditioning (HVAC), hot water (HW), lighting, home equipment, home electronics, renewable (RE), and occupancy pattern. R-BEET takes user inputs and various databases and, by calculation, produces a result in terms of annual energy consumption of a designed building resulting from the energy used by the building and its occupants compared to a baseline option. Further, R-BEET calculates the cooling energy demands by carrying out an energy balance based on monthly average weather conditions. The energy used for lighting, hot water, home appliances and electronics are also calculated. This is combined with information about system efficiencies in order to determine the energy consumption. Once the data has been input to R-BEET, it calculates:

1. Proposed HVAC system energy usage and efficiencies and provides energy requirements to maintain internal thermal conditions;
2. Lighting energy consumption of proposed design option compared to requirements on a standardised basis;
3. Hot water usage and needs;
4. Home appliances and electronics energy usages and requirements;
5. Aggregates the delivered energy by source;
6. Energy performance of the building compared to a benchmarked.

As it has been motioned in chapter four energy requirements due to heat gain through floor will not be included in the calculation because it is relatively small and difficult to calculate.

7.3.1 Energy requirements calculation

Methods used to calculate energy requirements are made based on the methods and equation explained in chapter five. As motioned in the previous chapters, energy requirements for thermal comfort accounts for more than 70% of the annual energy. Hence, further considerations have been taken to ensure that the energy calculation includes all the affecting factors. Energy requirements for cooling calculated based on degree day cooling defined by CIBSE explained in chapter five. The application of degree-days to cooling applications poses a number of steps, which are used in this thesis for maintaining simplicity. In their most general form, these steps involved:

1. The specific heat of air Cp in kJ/kgK
2. Mass flow rate $\dot{m}$ = in kW/K
3. The building time constant formula $\tau = \frac{c}{3600\, U'} = h$
4. Heat imparted to the air by the fan is given by $Q_{fan} = \frac{\dot{v}\, \dot{\Delta}\, P}{\eta_{fan}} = \dot{m} C_P (\theta_s - \theta_c) = K$
5. Sensible gains to the space (solar, people, lights and machines) = $\frac{Q_s}{\dot{m} C_P} = K$
6. fabric gain using equation $\frac{\acute{U}}{\dot{m} C_P} (\theta_{ao} - \theta_{ai}) = K$
7. Notional latent component using formula $K = \frac{2.5}{Q_{go}}$
    a. and $\overline{\Delta\acute{\theta}_L} = 2400 \times \frac{(\overline{g_o} - g_s)}{1 - e^{-k(\overline{g_o} - g_s)}} = K$
8. Mitigation due to overnight cooling $\frac{Q_c}{\dot{m} C_P} = \frac{\acute{U}}{24 \times 3600} \times \frac{e^{\frac{\theta_{ao}(night)}{\tau - 1}}}{\dot{m} C_P} = K$
9. Calculate the base temperature by subtracting the temperature differences from steps 3 to 6 from the indoor air set point temperature θ_b
10. Calculate cooling degree-days using $D_m = \frac{N\, (\overline{\theta}_{a,o} - \theta_b)}{1 - e^{-k(\overline{\theta}_{a,o} - \theta_b)}} = K.day$
11. Calculate the energy consumption of cooling system using $F = \frac{24 \times \dot{m}\, C_P\, D_m}{COP} = kW.h$
12. Calculate the optimum plant switch-on temperature

Other energy end user consumption is calculated based on occupancy and density of home machineries as follows:

- The required lighting energy E_L in kWh is calculated by the summation product of the installed power ***P(L)*** (in watts) of each luminaire, the operation time t_N (in hours), and a factor *F* as mentioned in Eq. 5.13 and Eq.5.14 (Chapter 5).
- Hot water calculation made based on BS6700, which recommends hot water at 60°C and estimated between 35 litres and 45 litres per person per day. The upper limit was selected for the calculation, as the use of domestic water in all GCC countries is higher than the average.
- Home appliances and electronics devices are calculated based on provided list of equipment type and energy consumptions.

7.4 Technological framework

In the early stages of a design, the use of sophisticated modelling tools appropriate for detailed design can be problematic. Experienced designers often fall back on their historical assumptions to provide initial design and budget input. An alternative approach to traditional rules of thumb is the use of simplified input spreadsheets. These have proven quick and easy to use for the early concept, and helpful for inexperienced engineers in evaluating the impact of assumptions vs. expectation. Therefore, Excel spreadsheets are used in this template because they are simple to use and a powerful calculation tool. The aim of this template is to show how a measurement and verification plan can be integrated into a framework to ensure the actual energy performance of a building is in line with expectation. The key technical framework of the designed template is made based on the environmental conditions, the building size and materials properties, equipment, home devices, occupancy and the uses of renewables.

The input data acts as the interface between the user and R-BEET calculation. As far as possible, the user is guided towards an appropriate data entry set in order to insure simplicity of using the template. Hence, the user interacts with the interface of the template, and sets up a model of the building, which describes its size, how it is used, how it is constructed and how it is serviced. The template will perform calculations based on input data and pre-stored data using the equations generated in chapter five and the current chapter. The user will not have access to these equations in order to prevent them from making accidental modifications. After the calculations are performed, the results and an output reports become accessible through the performance report sheet. The inputs to the energy calculation include:

- Physical configuration of the different areas of the building façades, glazing areas, geometry and orientation;
- Information about the proposed building cooling, lighting, and other building services systems;
- Installed home appliances and expected electronics devices load;
- Renewable energy considerations;
- Occupancy profile pattern.

Each task of the mentioned above list has been provided on a separate input sheet, the following sections of this chapter describe how these data are entered into R-BEET.

7.4.1 Envelope and orientation

The physical configuration of the building includes the façade areas, glazing areas and percentages, geometry and orientation, construction materials, and the materials U value is entered in the template through building envelope details sheet (BED) (Figure 7.3; Figure 7.4). This section of R-BEET will contribute the value of heat gain, which will be responsible for the size of the HVAC system and its energy consumption. The required entry data are:

- Façades areas, orientation from the north, percentage lazing;
- Opaque U values, glazing U values;
- Base line building construction elements details;
- Proposed building construction elements details;

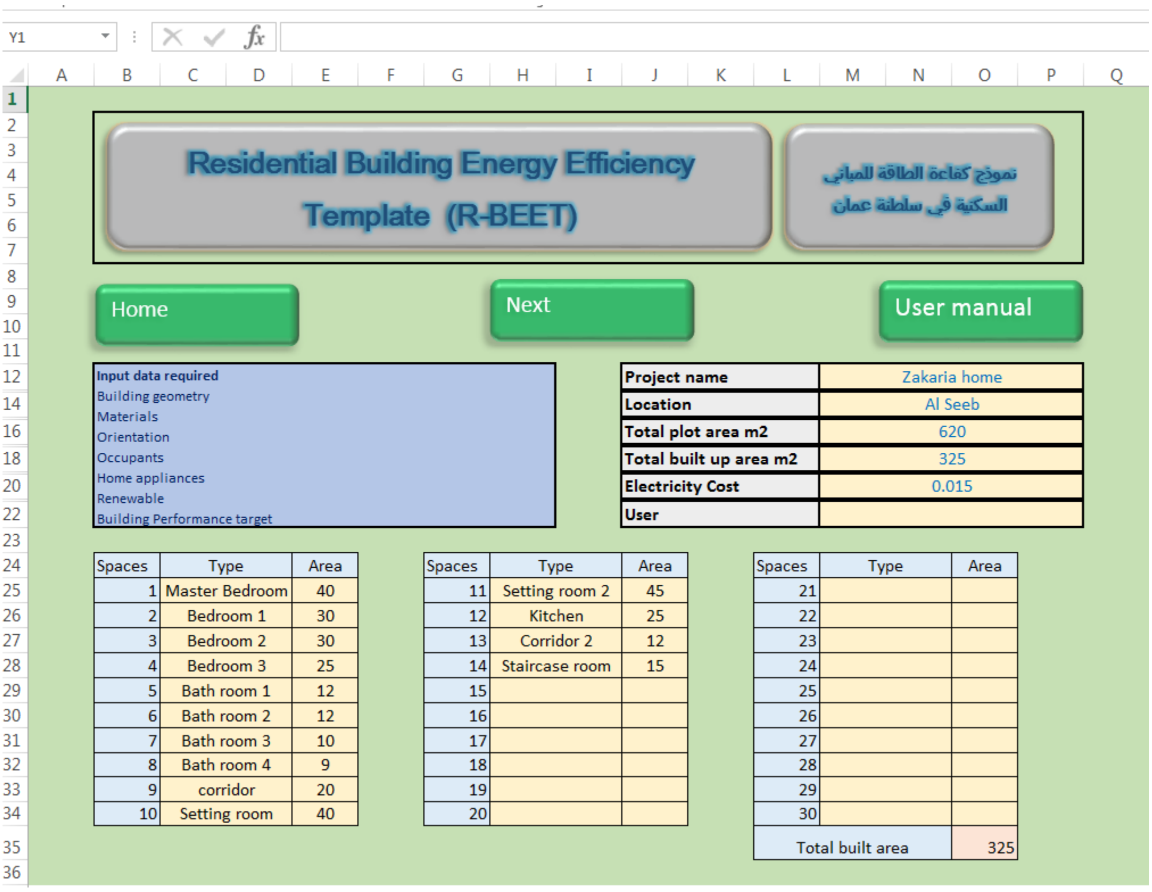
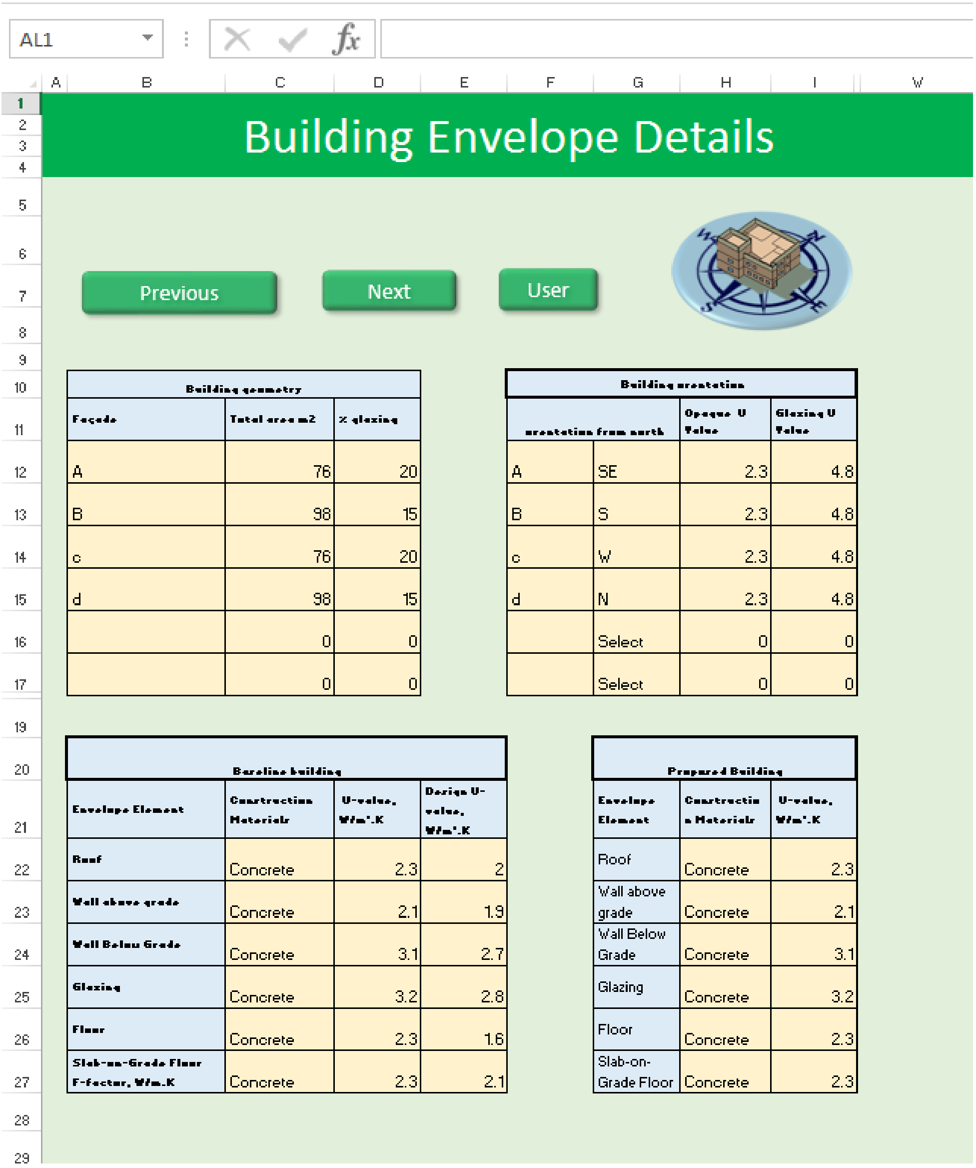


Figure 7.3: Building information data entry sheet



Building geometry		
Façade	Total area m2	% glazing
A	76	20
B	98	15
c	76	20
d	98	15
	0	0
	0	0

Building orientation			
orientation from north		Opaque U Value	Glazing U Value
A	SE	2.3	4.8
B	S	2.3	4.8
c	W	2.3	4.8
d	N	2.3	4.8
	Select	0	0
	Select	0	0

Baseline building			
Envelope Element	Construction Materials	U-value, W/m².K	Design U-value, W/m².K
Roof	Concrete	2.3	2
Wall above grade	Concrete	2.1	1.9
Wall Below Grade	Concrete	3.1	2.7
Glazing	Concrete	3.2	2.8
Floor	Concrete	2.3	1.6
Slab-on-Grade Floor F-factor, W/m.K	Concrete	2.3	2.1

Proposed Building		
Envelope Element	Construction Materials	U-value, W/m².K
Roof	Concrete	2.3
Wall above grade	Concrete	2.1
Wall Below Grade	Concrete	3.1
Glazing	Concrete	3.2
Floor	Concrete	2.3
Slab-on-Grade Floor	Concrete	2.3

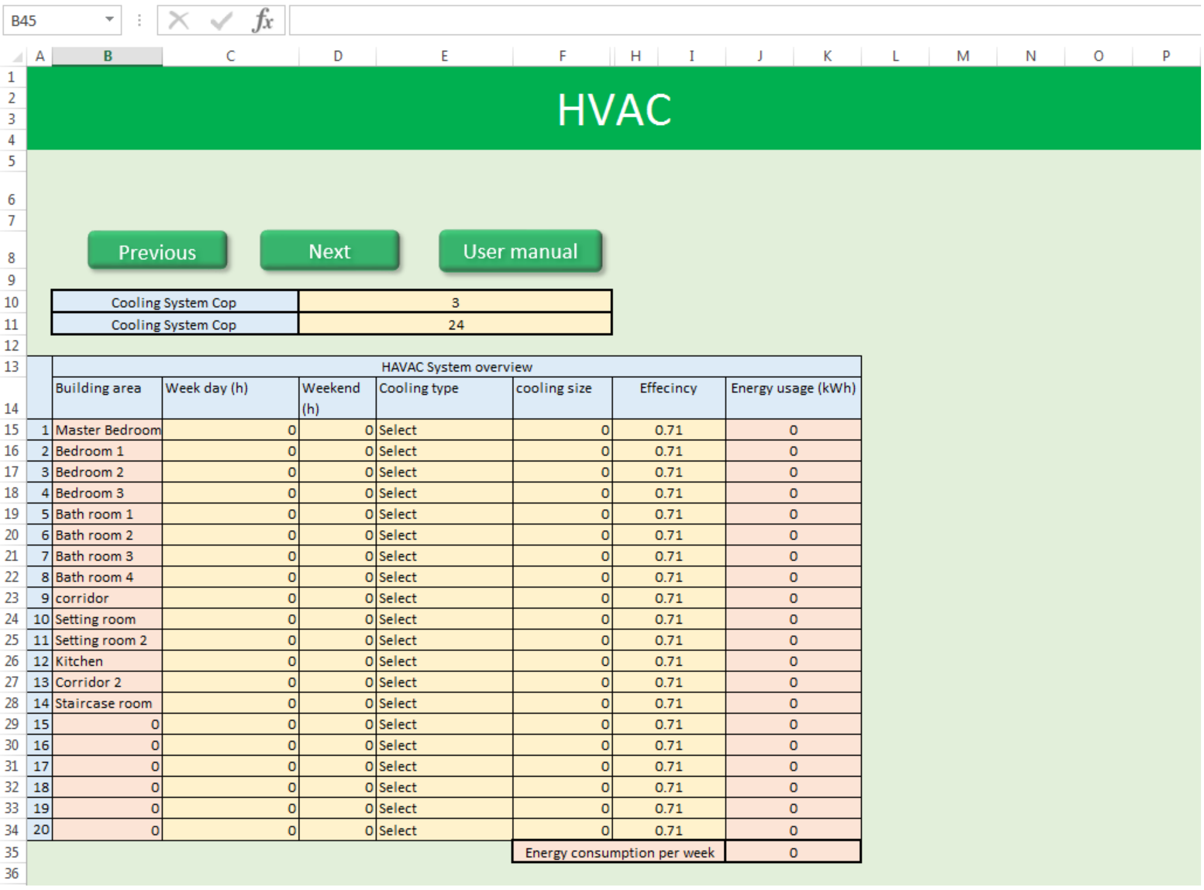
Figure 7.4: Building envelope data entry sheet

7.4.2 Building services data input sheets

There are three different sheets (Figures 7.5, 7.6, 7.7) dedicated for building services input data, which are:

- **Cooling set-points and set back temperatures:** cooling set-points define the conditions that the selected HVAC system will be assumed to maintain for the period defined by the usage schedules. For the unoccupied period, the system will be assumed to maintain the space at the setback temperature defined in the database.
- **Hot Water requirements:** for all occupied spaces, which is associated with the occupancy rather than the spaces where the hot water is accessed.

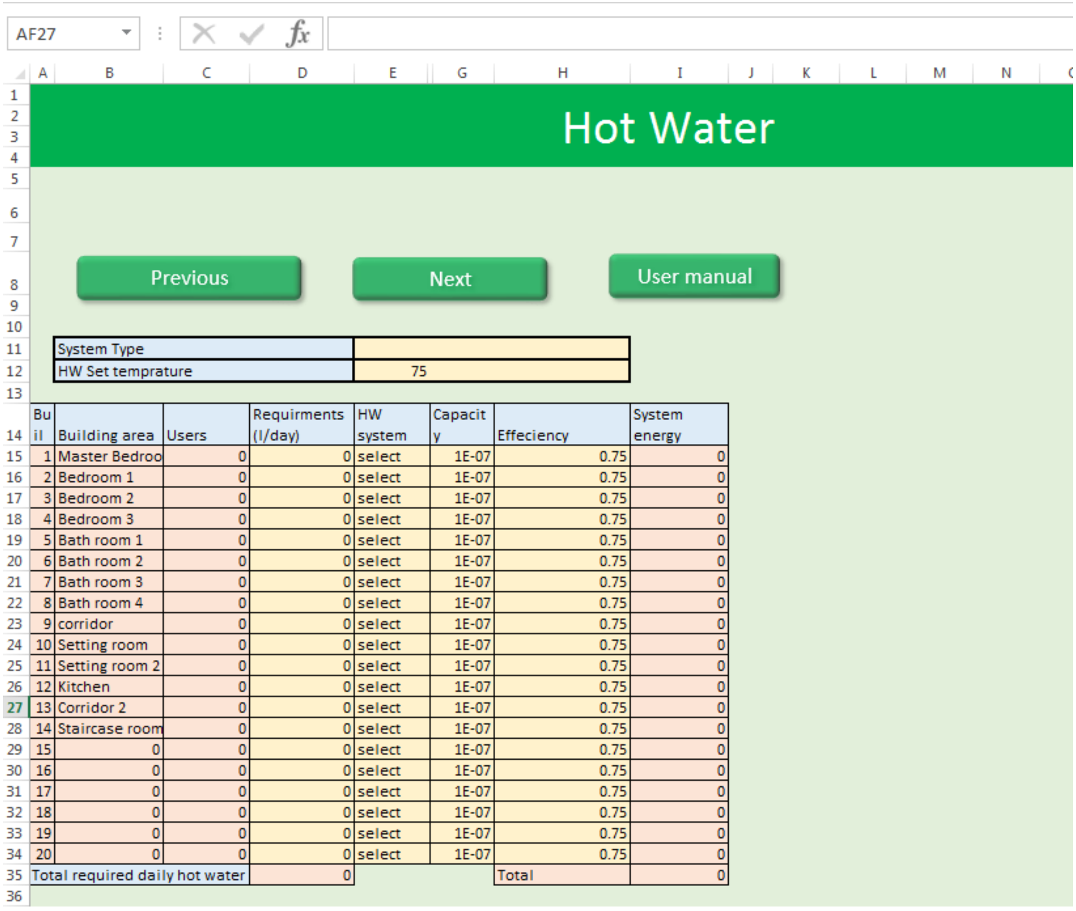
- **Lighting requirements:** includes the illuminance levels (in lux), which need to be maintained in each area. This level of illumination is then provided by the lighting system selected by the user. In addition, the lux levels, along with the user selected lighting system, are used to calculate the heat gains from lighting.



Cooling System Cop	3
Cooling System Cop	24

HAVAC System overview							
	Building area	Week day (h)	Weekend (h)	Cooling type	cooling size	Effecincy	Energy usage (kWh)
1	Master Bedroom	0	0	Select	0	0.71	0
2	Bedroom 1	0	0	Select	0	0.71	0
3	Bedroom 2	0	0	Select	0	0.71	0
4	Bedroom 3	0	0	Select	0	0.71	0
5	Bath room 1	0	0	Select	0	0.71	0
6	Bath room 2	0	0	Select	0	0.71	0
7	Bath room 3	0	0	Select	0	0.71	0
8	Bath room 4	0	0	Select	0	0.71	0
9	corridor	0	0	Select	0	0.71	0
10	Setting room	0	0	Select	0	0.71	0
11	Setting room 2	0	0	Select	0	0.71	0
12	Kitchen	0	0	Select	0	0.71	0
13	Corridor 2	0	0	Select	0	0.71	0
14	Staircase room	0	0	Select	0	0.71	0
15	0	0	0	Select	0	0.71	0
16	0	0	0	Select	0	0.71	0
17	0	0	0	Select	0	0.71	0
18	0	0	0	Select	0	0.71	0
19	0	0	0	Select	0	0.71	0
20	0	0	0	Select	0	0.71	0
					Energy consumption per week		0

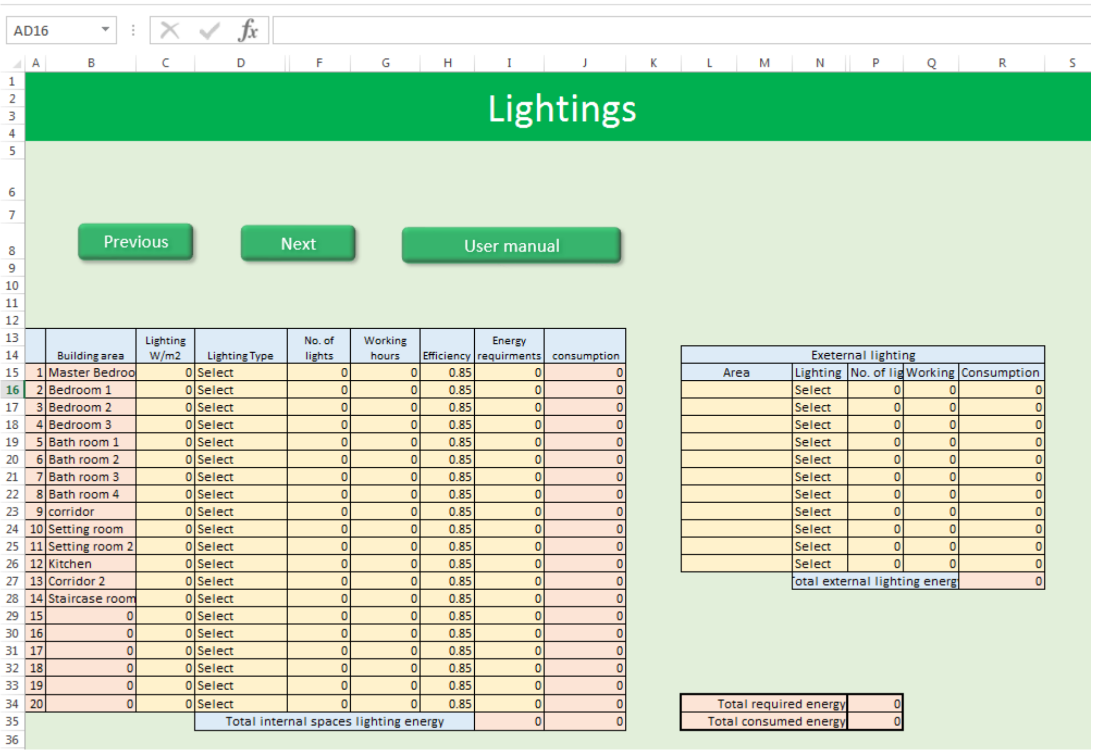
Figure 7.5: Building HVAC system data entry sheets



System Type	
HW Set temprature	75

Buil	Building area	Users	Requirments (l/day)	HW system	Capacity	Effeciency	System energy
1	Master Bedroo	0	0	select	1E-07	0.75	0
2	Bedroom 1	0	0	select	1E-07	0.75	0
3	Bedroom 2	0	0	select	1E-07	0.75	0
4	Bedroom 3	0	0	select	1E-07	0.75	0
5	Bath room 1	0	0	select	1E-07	0.75	0
6	Bath room 2	0	0	select	1E-07	0.75	0
7	Bath room 3	0	0	select	1E-07	0.75	0
8	Bath room 4	0	0	select	1E-07	0.75	0
9	corridor	0	0	select	1E-07	0.75	0
10	Setting room	0	0	select	1E-07	0.75	0
11	Setting room 2	0	0	select	1E-07	0.75	0
12	Kitchen	0	0	select	1E-07	0.75	0
13	Corridor 2	0	0	select	1E-07	0.75	0
14	Staircase room	0	0	select	1E-07	0.75	0
15	0	0	0	select	1E-07	0.75	0
16	0	0	0	select	1E-07	0.75	0
17	0	0	0	select	1E-07	0.75	0
18	0	0	0	select	1E-07	0.75	0
19	0	0	0	select	1E-07	0.75	0
20	0	0	0	select	1E-07	0.75	0
Total required daily hot water			0			Total	0

Figure 7.6: Domestic hot water data entry sheets



	Building area	Lighting W/m2	Lighting Type	No. of lights	Working hours	Efficiency	Energy requirments	consumption
1	Master Bedroo	0	Select	0	0	0.85	0	0
2	Bedroom 1	0	Select	0	0	0.85	0	0
3	Bedroom 2	0	Select	0	0	0.85	0	0
4	Bedroom 3	0	Select	0	0	0.85	0	0
5	Bath room 1	0	Select	0	0	0.85	0	0
6	Bath room 2	0	Select	0	0	0.85	0	0
7	Bath room 3	0	Select	0	0	0.85	0	0
8	Bath room 4	0	Select	0	0	0.85	0	0
9	corridor	0	Select	0	0	0.85	0	0
10	Setting room	0	Select	0	0	0.85	0	0
11	Setting room 2	0	Select	0	0	0.85	0	0
12	Kitchen	0	Select	0	0	0.85	0	0
13	Corridor 2	0	Select	0	0	0.85	0	0
14	Staircase room	0	Select	0	0	0.85	0	0
15	0	0	Select	0	0	0.85	0	0
16	0	0	Select	0	0	0.85	0	0
17	0	0	Select	0	0	0.85	0	0
18	0	0	Select	0	0	0.85	0	0
19	0	0	Select	0	0	0.85	0	0
20	0	0	Select	0	0	0.85	0	0
			Total internal spaces lighting energy				0	0

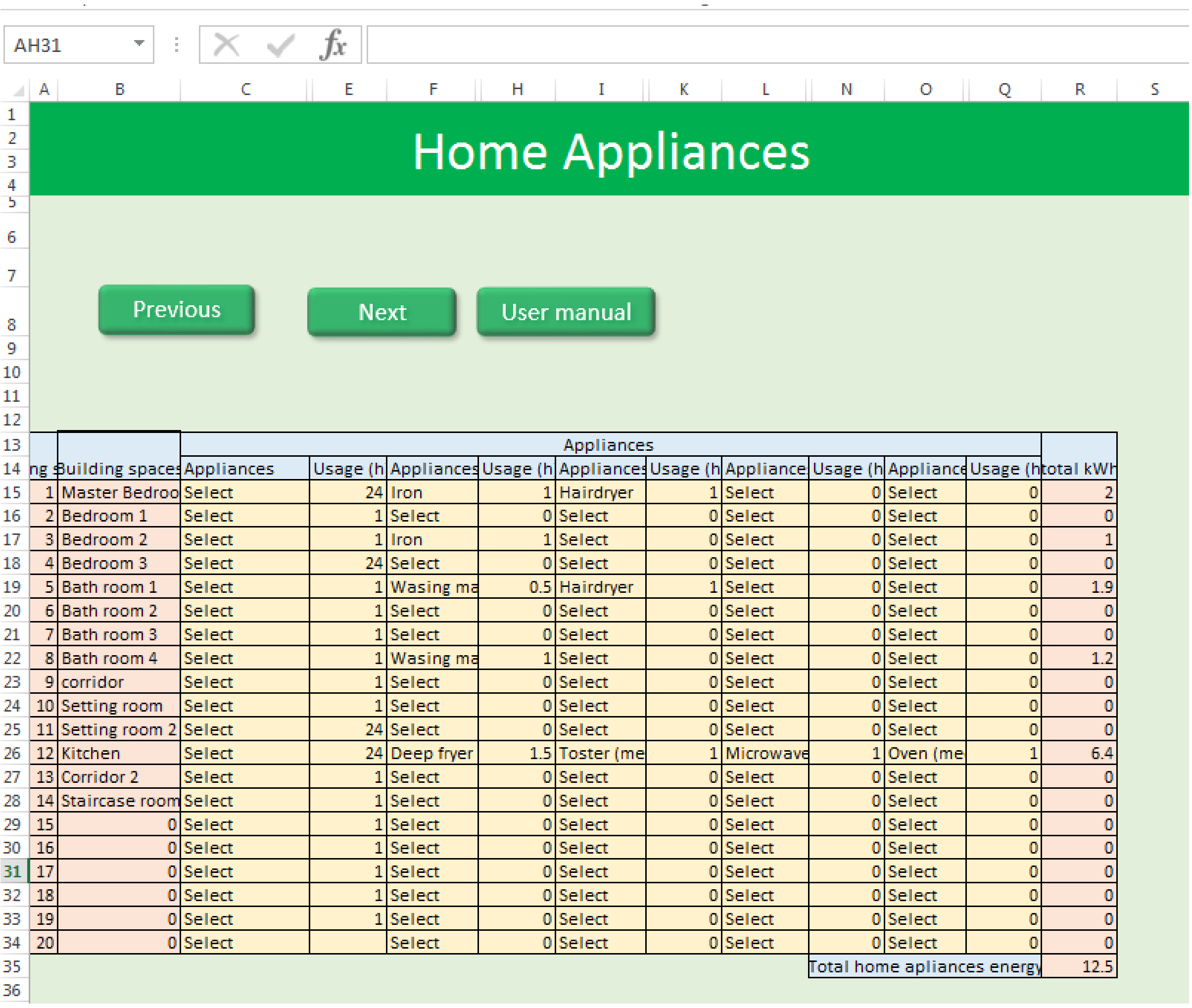
Exeternal lighting				
Area	Lighting	No. of lig	Working	Consumption
	Select	0	0	0
	Select	0	0	0
	Select	0	0	0
	Select	0	0	0
	Select	0	0	0
	Select	0	0	0
	Select	0	0	0
	Select	0	0	0
	Select	0	0	0
	Select	0	0	0
	Select	0	0	0
	otal external lighting energ			0

Total required energy	0
Total consumed energy	0

Figure 7.7: Building lighting data entry sheets

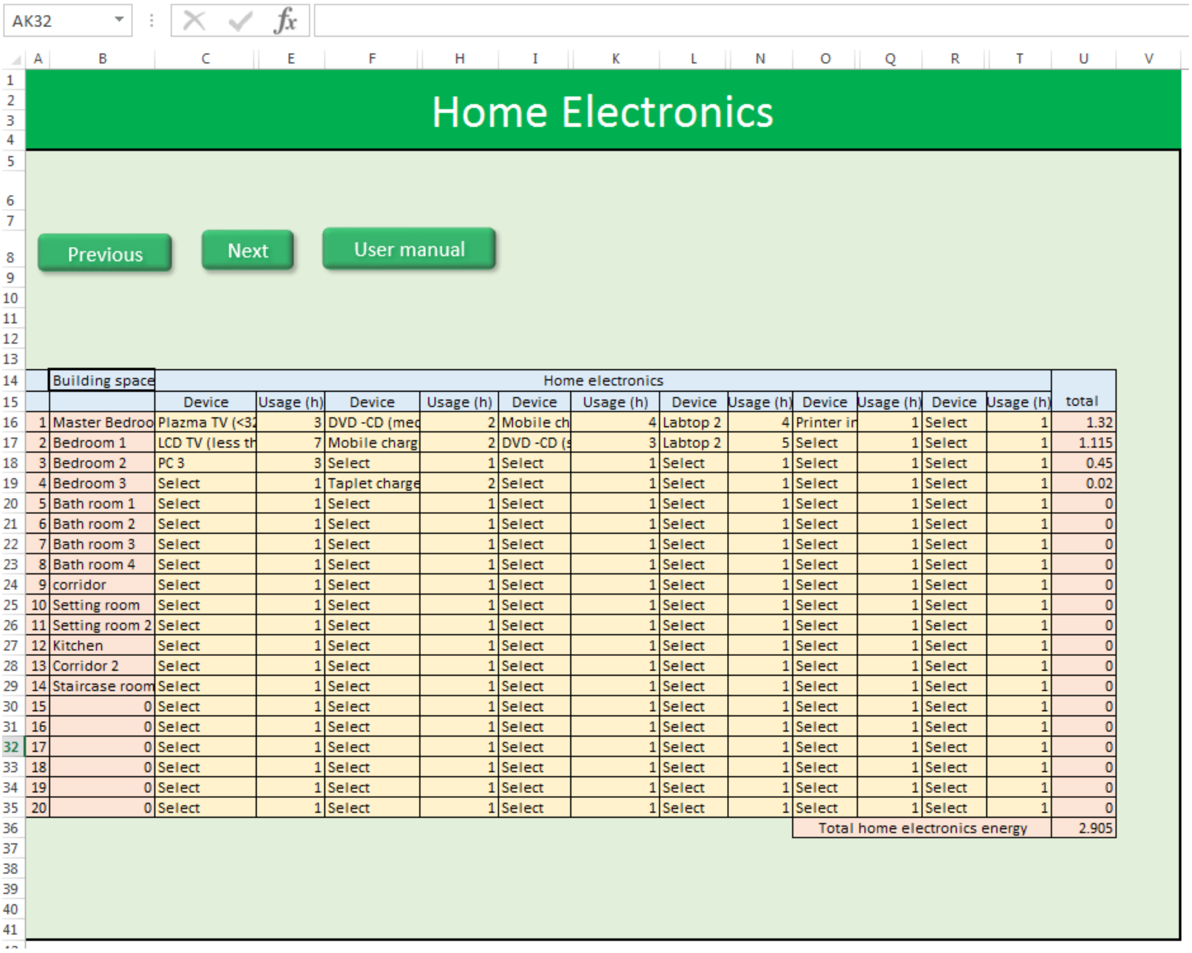
7.4.3 Home appliances and electronics

The energy demand for residential appliances and equipment is increasing with rising incomes and the improvement of lifestyle that has resulted in more appliances being used in the home. R-BEET contains two spreadsheets for home appliances energy input (Fig. 7.8 and 7.9). These spreadsheets are named home appliances, which is dedicated for home machineries such as air-conditioning, wash machines, cold appliances and kitchen appliances, and the input screen for home electronics including computers, printers, TV, mobile chargers etc.



		Appliances										
ng s	Building spaces	Appliances	Usage (h	Appliances	Usage (h	Appliances	Usage (h	Appliance	Usage (h	Appliance	Usage (h	total kWh
1	Master Bedroo	Select	24	Iron	1	Hairdryer	1	Select	0	Select	0	2
2	Bedroom 1	Select	1	Select	0	Select	0	Select	0	Select	0	0
3	Bedroom 2	Select	1	Iron	1	Select	0	Select	0	Select	0	1
4	Bedroom 3	Select	24	Select	0	Select	0	Select	0	Select	0	0
5	Bath room 1	Select	1	Wasing ma	0.5	Hairdryer	1	Select	0	Select	0	1.9
6	Bath room 2	Select	1	Select	0	Select	0	Select	0	Select	0	0
7	Bath room 3	Select	1	Select	0	Select	0	Select	0	Select	0	0
8	Bath room 4	Select	1	Wasing ma	1	Select	0	Select	0	Select	0	1.2
9	corridor	Select	1	Select	0	Select	0	Select	0	Select	0	0
10	Setting room	Select	1	Select	0	Select	0	Select	0	Select	0	0
11	Setting room 2	Select	24	Select	0	Select	0	Select	0	Select	0	0
12	Kitchen	Select	24	Deep fryer	1.5	Toster (me	1	Microwave	1	Oven (me	1	6.4
13	Corridor 2	Select	1	Select	0	Select	0	Select	0	Select	0	0
14	Staircase room	Select	1	Select	0	Select	0	Select	0	Select	0	0
15	0	Select	1	Select	0	Select	0	Select	0	Select	0	0
16	0	Select	1	Select	0	Select	0	Select	0	Select	0	0
17	0	Select	1	Select	0	Select	0	Select	0	Select	0	0
18	0	Select	1	Select	0	Select	0	Select	0	Select	0	0
19	0	Select	1	Select	0	Select	0	Select	0	Select	0	0
20	0	Select		Select	0	Select	0	Select	0	Select	0	0
									Total home apliances energy			12.5

Figure 7.8: Home appliance and electronics sheets



	Building space	Home electronics												total
		Device	Usage (h)	Device	Usage (h)	Device	Usage (h)	Device	Usage (h)	Device	Usage (h)	Device	Usage (h)	
1	Master Bedroo	Plazma TV (<32	3	DVD -CD (med	2	Mobile ch	4	Labtop 2	4	Printer in	1	Select	1	1.32
2	Bedroom 1	LCD TV (less th	7	Mobile charg	2	DVD -CD (s	3	Labtop 2	5	Select	1	Select	1	1.115
3	Bedroom 2	PC 3	3	Select	1	Select	1	Select	1	Select	1	Select	1	0.45
4	Bedroom 3	Select	1	Taplet charge	2	Select	1	Select	1	Select	1	Select	1	0.02
5	Bath room 1	Select	1	Select	1	Select	1	Select	1	Select	1	Select	1	0
6	Bath room 2	Select	1	Select	1	Select	1	Select	1	Select	1	Select	1	0
7	Bath room 3	Select	1	Select	1	Select	1	Select	1	Select	1	Select	1	0
8	Bath room 4	Select	1	Select	1	Select	1	Select	1	Select	1	Select	1	0
9	corridor	Select	1	Select	1	Select	1	Select	1	Select	1	Select	1	0
10	Setting room	Select	1	Select	1	Select	1	Select	1	Select	1	Select	1	0
11	Setting room 2	Select	1	Select	1	Select	1	Select	1	Select	1	Select	1	0
12	Kitchen	Select	1	Select	1	Select	1	Select	1	Select	1	Select	1	0
13	Corridor 2	Select	1	Select	1	Select	1	Select	1	Select	1	Select	1	0
14	Staircase room	Select	1	Select	1	Select	1	Select	1	Select	1	Select	1	0
15	0	Select	1	Select	1	Select	1	Select	1	Select	1	Select	1	0
16	0	Select	1	Select	1	Select	1	Select	1	Select	1	Select	1	0
17	0	Select	1	Select	1	Select	1	Select	1	Select	1	Select	1	0
18	0	Select	1	Select	1	Select	1	Select	1	Select	1	Select	1	0
19	0	Select	1	Select	1	Select	1	Select	1	Select	1	Select	1	0
20	0	Select	1	Select	1	Select	1	Select	1	Select	1	Select	1	0
										Total home electronics energy				2.905

Figure 7.9: Home appliance and electronics sheets

7.4.4 Renewable energy consideration

Despite the fact that renewable energy is not in use in the current residential buildings in Oman, the template has considered the application of renewables. The considered RE applications in R-BEET are limited to solar hot water heater and PV systems. Selection of these type of RE is made based on the successes of their applications on the references buildings. Accordingly, renewable energy systems used in reference LCBs were included in the template (Fig. 7.10). Since RE systems used in reference to LCBs were tested and have demonstrated their capabilities to reduce the use of conventional energy, therefore R-BEET included these systems only in the calculation of RE and overall energy uses. The template gives the user the choice of using onsite RE or not. If use of RE is selected then the user will have to select type and size of RE from the available data in the template.

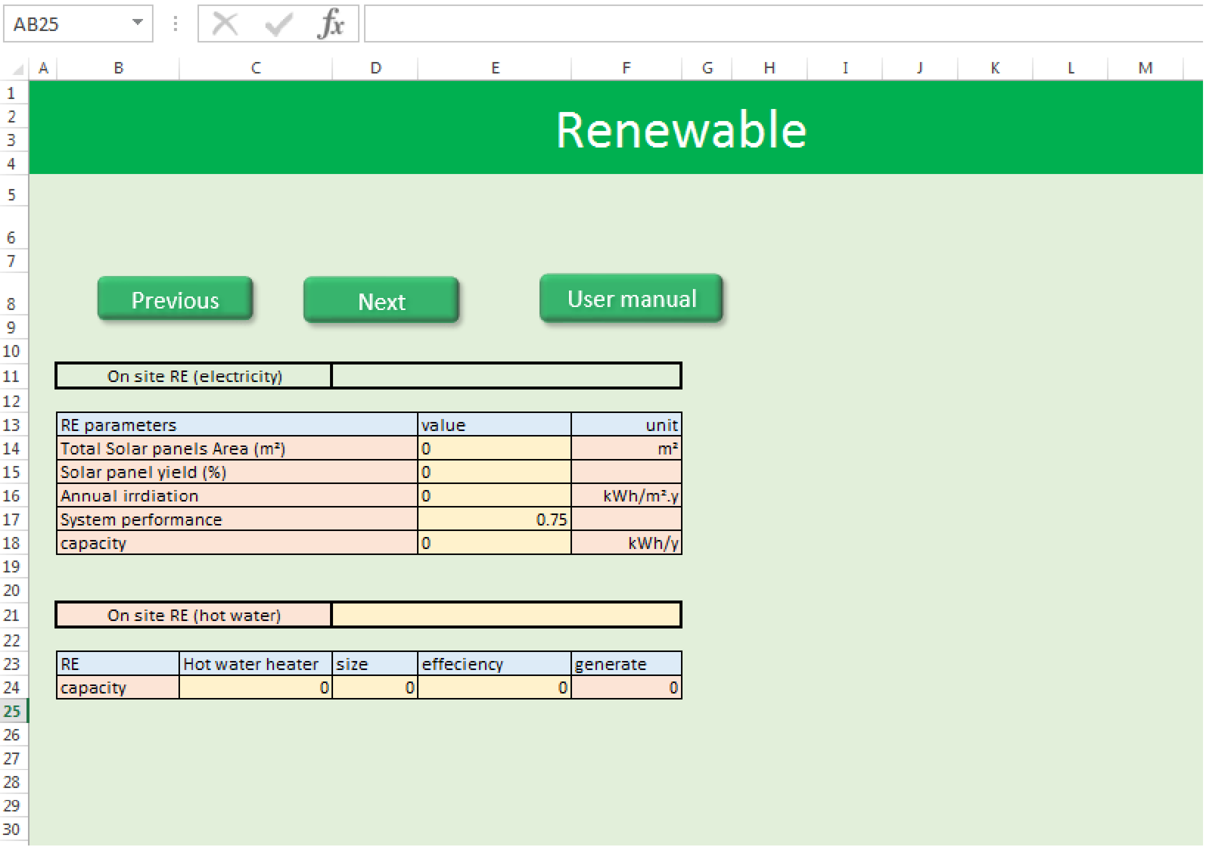


Figure 7.10: Renewables data entry sheet

7.4.5 Occupancy

Occupancy density and rate play an important role in building, as it directly affects both internal gains and energy use. The occupancy density and schedules of occupancy per rooms are used to calculate the internal heat gains from people. Heat gain per person is assumed to be 100 W. The input data for occupancy in R-BEET are entered through the occupancy spreadsheet. The building zones nominated in the start spreadsheet will appear in the window where the user will have to enter the number of occupants and their time profile in each space (Fig. 7.11).

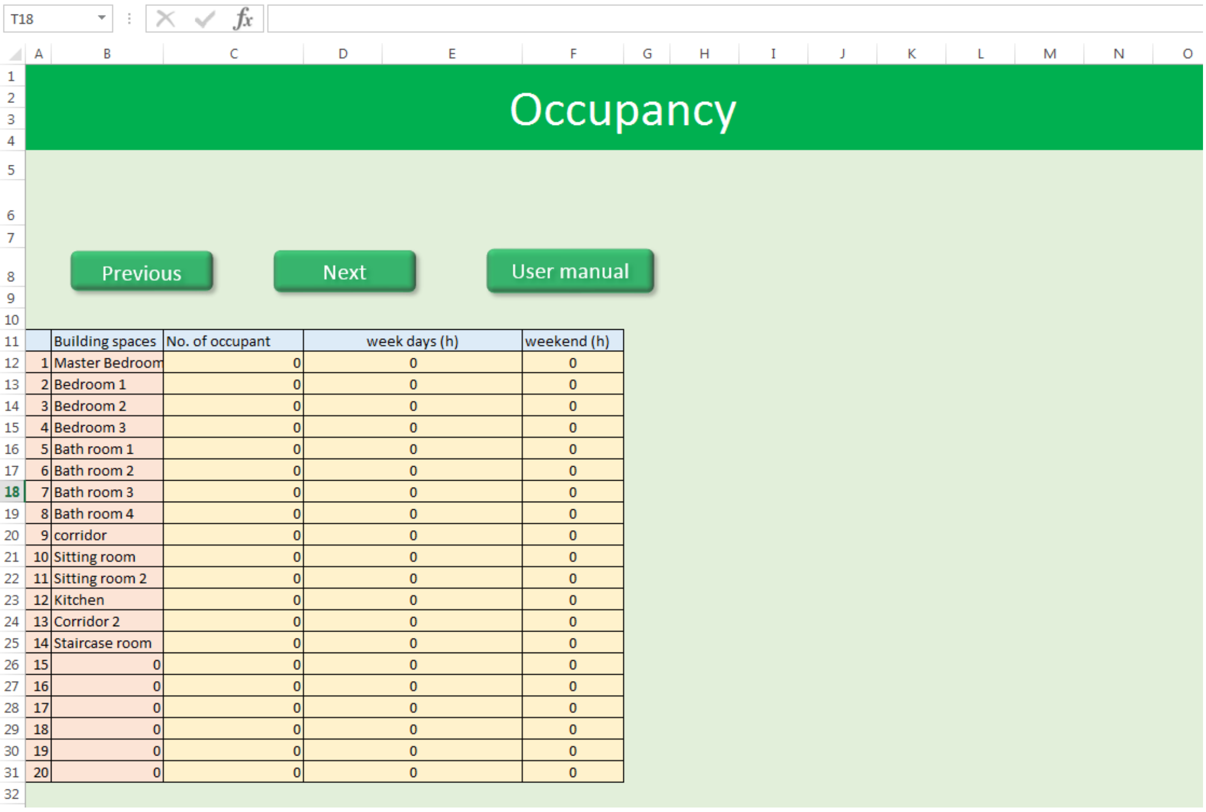


Figure 7.11: Building occupancy profile

7.4.6 Template output

The basic calculation scheme is straightforward where it calculates monthly and annual energy consumption per home tasks based on two scenarios. The first scenario represents energy requirements of the building, which refers to the building energy needs based on its design orientation and the use of efferent home appliances that have been used in the reference LCBs. The second scenario shows the consumption of the building based on materials, and home equipment based on the data entered by the user. The graphical output of the template (Fig. 7.12) gives the comparison of these two scenarios in order to identify each home-task energy consumption for further improvements or modifications on the building input data.

Figure 7.12: Sample template output

7.5 Validating the Concept of the template

The R-BEET procedure has been applied to the reference conventional buildings in order to validate its capability. Based on the information from the monitoring and audit, the energy consumption of the reference CBs was estimated using the template in two scenarios as built and best practice scenario (Table 7.2). These results which obtained from R-BEET were compared to measured energy consumptions. As built energy consumptions refers to energy consumptions of CBs considering actual building materials, orientation and home appliances, while best practice energy consumption scenario refers to CBs energy consumptions obtained by changing building orientation and the use of more efficient home appliances under the same usage profiles.

Reference buildings	**Baseline energy consumptions kWh/year**	**As constructed energy consumptions kWh/year**	**% CO_2 reduction using the template**
CB1	15405.37	19267.6	13.20
CB2	17596.86	20648.8	14.78
CB3	30684.81	33254.37	7.72
CB4	16693.84	19998.11	16.52

Table 7.2: Summary of R-BEET energy consumption results

The template has shown acceptable results for building CB1 and CB3 since best practice energy was lower than measured. The other two buildings results considered less accurate because all results for both houses were more than the measured (Figure 7.13). However, the less accurate of results for CB2 and CB4 can be referred to the fact that the measured energy data have not matched the energy audits conducted on these buildings as explained in chapter five where these two buildings were disregarded from IES modelling. Therefore, this show more confidence on the applicability of R-BEET.

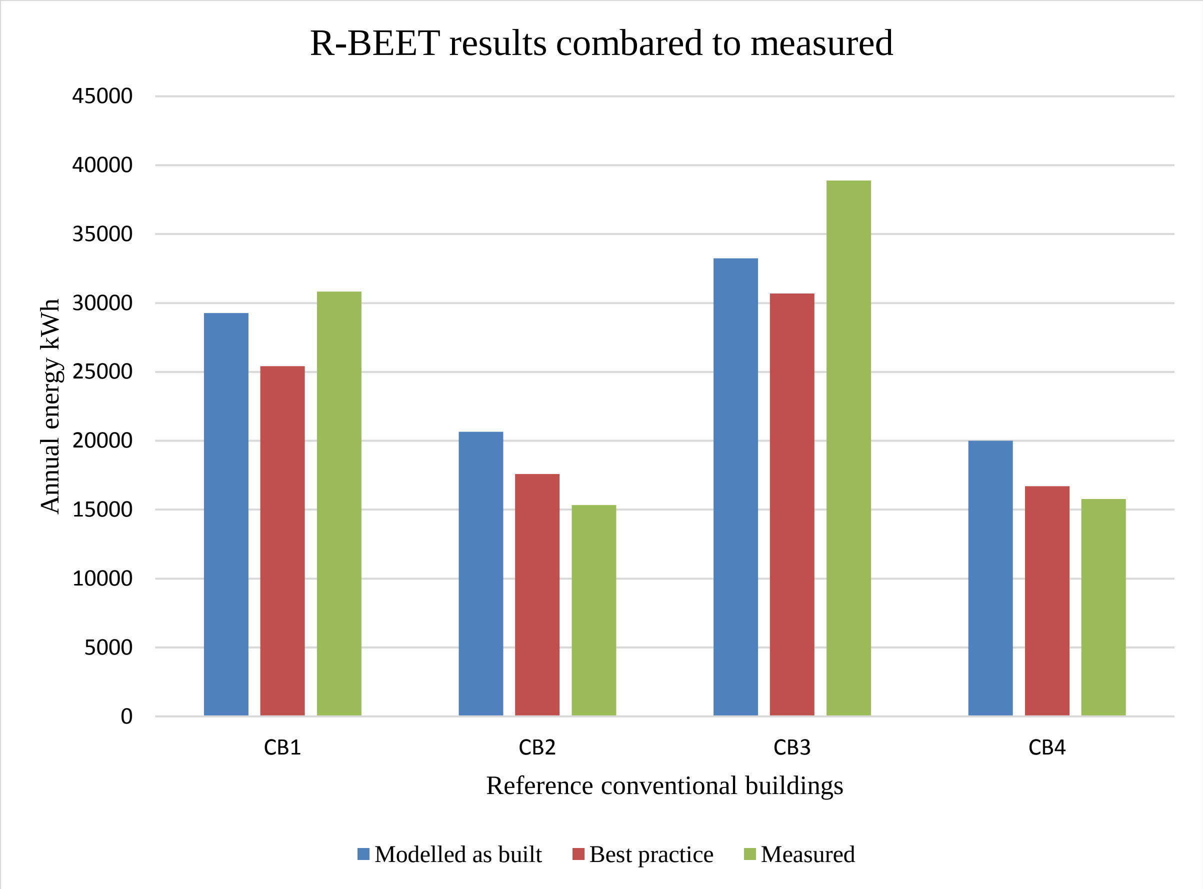


Figure 7.13: Energy report for reference CBs prepared by R-BEET

Generally, R-BEET results are tolerable compared to monthly historical data for 2014. Considering energy consumptions results for CB1 and CB3 obtained using R-BEET the percentage errors calculated to be between 5% and 15%. The difference between actual and calculated energy consumption is called the 'energy performance gap' (Brom, Meijer and Visscher, 2017). In the past 20 years a number of studies provided explanations for the potential energy performance gap between calculated and actual energy performance of buildings (Ingle et al., 2014). Many researchers and governmental institutions think the occupant is the main cause of this gap (Brom, Meijer and Visscher, 2017). In this research, possible explanations for this gap are construction materials properties, home appliance age and usage conditions, excessive simplification in simulation models and occupant behaviour. However, despite this, the findings from this results are likely to be acceptable because in reality it is not possible to achieve 100 % absolute similarity between measured and modelled energy consumption of buildings due to their real-life complexity mentioned in chapter three.

Reference buildings	Actual energy consumptions	As constructed energy consumptions by R-BEET	% of errors
CB1	30837	29267.6	5
CB2	15343	20648.8	34
CB3	38890	33254.37	15
CB4	15768	19998.11	26

Table 7.3: Percentage errors

Researchers stated that modelling of home energy use tends to overestimate actual energy consumption, with average modelled consumption across house groups often 20–50% higher than observed averages (Ingle *et al.,* 2014). Based on the application of R-BEET in this research, energy consumption obtained for both scenarios proved its ability to show a tangible deference in energy usage of two design options. Hence it can be used as energy calculator tool at design stage, selection of energy efficient building materials or supporting a decision for building energy policy.

7.6 Recommendations for potential application of the template

Thus, this template can be beneficial for the environment of Oman to offer strategies, which could well address some of the salient energy consumption agents in residential building as follows:

- R-BEET aimed at offering low carbon-emitting building could be used for humid, sultry weather, which is found persisting in Sultanate of Oman and use of energy-saving, heat reducing strategies in these domains such that over time, it is possible to offer low carbon strategy based on the results and outcomes of these studies.
- Secondly, it is needed to consider what are the major issues with regard to increased consumption in buildings, especially single-family buildings in Oman as well as villas, flats and apartments, how heat and energy released through wanton use of energy could be reduced and also, more importantly, the best low carbon-solutions and options could be made that addresses resultant issues and offers remedial solutions for issues surrounding low carbon template usage.
- Further, and more importantly, it is needed to consider, in the Omani context, whether, how and the extent to which, given the volatile nature of climatic and other endogenous

and exogenous impacts in the Omani context, determine how the deployment of R-BEET could well be institutionalised, deployed and effectuated in the Omani context in the short, medium and long term of its use, and how its main aims, goals and objectives for deployment could optimally be gained.

- Since the Residential Building Energy Efficiency Template needed to form the core arguments of the thesis study, it is also needed to be argued what are its chief advantages, benefits and resource building, especially in terms of its technical, techno-commercial, techno-economic and importantly, techno-environmental and how could optimal gains/benefits and minimal losses/drawbacks be gained over time.
- Next, it is needed to state the major barriers, challenges, roadblocks and obstacles in the use of R-BEET in this region, to consider the special characteristics of the hot, humid climates prevailing in this region and how the best of R-BEET could help in firstly, effectively addressing, and secondly, resolving overly demand and high consumption levels of energy in the Omani context, especially for the short, medium and long term.
- The above must be considered in the light of fact that, in as much as the Omani regime is considered, there is indeed a paucity of policy frameworks or a lack of robust Policy Instruments, which seek to support deployment of Renewable Energy projects and, more importantly, the fact that Oman subsidises fossilised fuels which render electrical –based energy use rather costly. Furthermore, according to the Oman Electricity and Heat Statistics, Final Consumption of Electricity in Residential Buildings is much higher than consumption in other construction areas, especially in residential buildings.

7.7 Chapter summary

The availability of an energy calculation tool will help in evaluating deferent design options in order to select a better strategy for low energy building. Consequently, this will lead to buildings meeting expected performance targets and reduce the high energy construction of the buildings sector such as in the case of Oman. This chapter discussed the development of a residential building energy template created in an Excel workbook. The template generates an energy consumption report that show the monthly and annual consumption of a building based on user data input. Some of the inputs are standardised to allow consistent comparisons for building energy for rating purposes in new and existing buildings. It can calculate the energy demands of each space in the building according to the activity occupancy and home appliances. In more detail, the R-BEET can be used to:

1. Develop a methodology of calculation of the integrated energy performance of buildings;
2. Set minimum requirements for the energy performance of new and existing buildings;
3. Ensure that those requirements for the energy performance are met in new buildings;
4. Develop energy certification of buildings;
5. Establish standard for low carbon building in the Sultanate;
6. Determine CO_2 emissions of operating a building;
7. Determines, on a similar basis, the CO_2 emissions of a reference building, which has fixed ventilation and cooling conditions and space and water heating fuel.

Furthermore, the template has been tested on reference CBs and found to be acceptable, and hence can be used for the purpose it has been designed for.

8 Roadmap for Oman's LCB strategy

8.1 Introduction

The building sector is linked to climate change policy through GHG emissions of the energy used in building stock (Transition to Sustainable Buildings, 2017). Like every country, the Sultanate of Oman needs to take action now to plan for low carbon transition in order to reduce its CO_2 emission level. This will require major changes to the use and supply of energy to ensure secure supplies of energy in a way that maximises its benefits and minimizes its effects. Therefore, this chapter, suggests a roadmap to implement best practice low carbon residential buildings in Oman as a pathway for the country to achieve low carbon transition in the residential sector. This roadmap plan is drafted based on the EEMs examined in chapters five and six, in addition to EEM6 and EEM9 (energy efficiency measures due to insulation and renewables) which are examined in this chapter. It identifies the vision, action required and suggested implementation method (Figure 8.1). The essence of the provided roadmap to conserve energy in dwellings is that reducing energy consumption of the building sector can result in much greater reductions than what the other sectors may contribute to climate change.

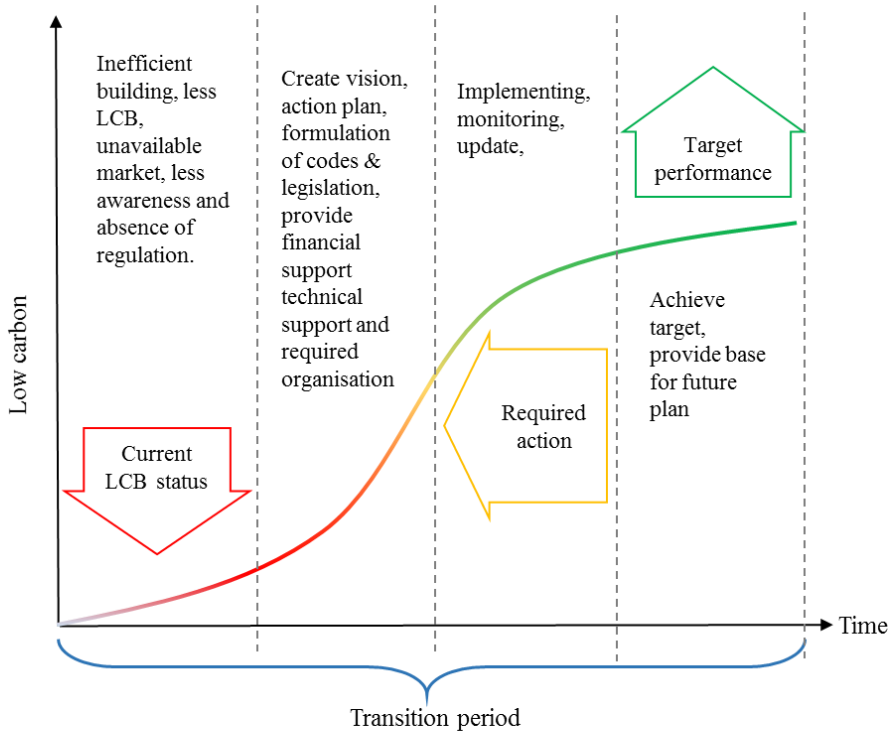


Figure 8.1: A roadmap to best practice LCB

8.2 Low carbon residential building roadmap overview

The low carbon energy roadmap refers to a shift from conventional buildings based on fossil fuels to a building sector based on less conventional energy sources or on renewables and implements energy efficiency measures. Low energy buildings transitions occur first in the developing countries from results based on observations and drivers (Urban, 2016). Energy use in buildings depends on a combination of architecture, building energy systems design and efficient operations. This requires LCB adopted architecture and engineering designs, good quality materials and construction practices and intelligent operation of the building.

A good LCB strategy for a developing country has to be climate-friendly, low carbon, follow successful sustainable development adopted from developed countries, avoid negative effects of climate change and adopt patterns of low carbon consumption and production. Furthermore, it needs to encourage the appropriate use of renewables in order to reduce the consumption of conventional energy sources based on a targeted plan. For example, the EU announced in March 2015 to reduce at least 40% of domestic greenhouse gas emissions by 2030 compared to 1990 levels. This target reduction was supported by a set of regulatory frameworks, i.e. the Energy Performance of Buildings Directive 2010/31/EU, which was originally published in 2002.

8.3 Roadmap towards low carbon residential building in Oman

The sector's developments in the past decades have shown negative trends in energy conservation resulting in in several rapidly changing aspects in the country. More than half of the current Oman building stock was constructed after 2010 so they will still be standing in 2050. Most buildings last for decades, some may last for centuries, however, the life cycle of buildings in developing countries is shorter than that found in a developed country. Building involves many parties and its life cycle in Oman is between 30 and 50 years. The potential energy consumption reduction by implementing EEMs has been estimated in chapter five; hence, considering the EU's strategy to reduce domestic building energy, a convenient energy reduction target for residential building in Oman should be 25% to 50% within a timeframe of 30 years.

Therefore, the first attribute of a low carbon roadmap in transforming the building sector to low carbon is to reduce energy use by setting target performance and a target transformation period. Key required actions include the following:

- Develop standards and regulations;
- Increase the awareness of the public and the industry sector;
- Introduce high-efficiency home appliances and high-efficiency lighting devices ;
- Consider the application of insulation materials;
- Implement the use of simulation software for optimizing building design and operation;
- Develop low-cost, easy to install, renewable energy solutions.

The main barriers and suggested solutions have been discussed in chapter four so in this chapter a transformation strategy will be devised in order to provide a pathway for the residential building sector to smoothly shift to low carbon (Table 8.1).

Barriers	**Required solutions**	**Suggested transformation**
Weather and climate changes challenges	Formulation of codes, climate adaptive design, and renewable energy initiatives	Application of insulation and renewables.
Social/cultural barriers	Introduce culture of LCB in the society, increase public awareness and participation	Occupants' lifestyle adjustments and building energy managements.
Economic barriers	Provide funds to motivate owners to implement sustainable development strategies	Revised electricity tariff, provide support to renewables.
Limited governmental and technical drivers	Provide the required legislation, increase R&D and technical support.	Create building energy vision and plan.

Table 8.1: LCB roadmap suggested transformations

8.3.1 Sustainable standards and regulation update

In 2014 Oman ranked in the top 20 countries for CO_2 emissions per capita where buildings consumed more than 48% of the total country energy consumption. It was then clearly perceived that buildings as well as other developments could lead to environmental damage through inefficient use of resources and poor management. Therefore, there was the need to minimize carbon emissions from buildings as well as ensure that planning policies facilitated protection and improvement of both the built and natural environment. These polices entailed reducing carbon emissions from buildings through the application of codes and standards, i.e.

those that are applied in developed countries (Table 8.2). In this regard, it was advisable to consider these codes as an exemplar for devising codes for Oman.

Code of practice	**International example**	**Country**	**Objectives of implementation**
Building code	International Energy Conservation Code (IECC)	USA	The establishment of minimum design and construction requirements for energy efficiency.
Energy regulation	Part L. Conservation of fuel and power	UK	To set out the requirements for the target of LCB such as sizes of openings and insulations, etc.
Building energy rating and certification	BREEAM	UK	Raise awareness amongst owners, occupiers, designers and operators of the benefits of taking a sustainability approach.
Home appliances labelling	Energy Star	USA	To provide consumers with information about energy consumption, efficiency and operating costs of home appliances.
Renewables Regulation	The Public Utility Regulatory Policies Act 1978 (PURPA)	USA	To create a market for power from non-utility power producers.

Table 8.2: Sample of international codes and their objectives

8.4 Technical recommendation for application of LCB strategy

Providing a comfortable and healthy interior environment is one of the core functions of building energy systems and accounts for about a third of total building energy use. New construction methods and materials besides technologies for heating, cooling and ventilation not only improve a building's efficiency but can also improve the lifestyle of occupants, providing better control and reducing unwanted heat associated with variations. Opportunities for improvements were classified in the following basic categories:

- Improve the building envelope;
- Manage heat loss through ventilation;
- Improve space conditioning techniques;
- Improve lighting systems and control;
- Improve building system level.

8.4.1 The Building Envelope

The envelope's elements – walls, foundation, roof and windows – separate the interior environment from the exterior environment of the building. The insulating properties of the building envelope and construction quality control heat and moisture flows to the building. Furthermore, the colour of the building envelope will contribute to its reflection and absorption of heat from solar radiation. Also, heat transfer through building openings such as windows and external doors affects energy requirements for cooling. A large cooling load in residential buildings results from window heat gains. Hence, the required qualities of a window are:

- Attract lighting levels without glare, high levels of thermal insulation, block sun's rays when it increases cooling loads;
- Low emissivity;
- Glass coatings to reduce absorption and re-emission of infrared light;
- Windows with multilayers of glass.

The walls, roofs and foundations of buildings also control the flow of heat, moisture and air to the internal space of the building. In situations where air conditioning is a significant load, the roof should reflect radiation; hence ideal materials for the building shell would comprise:

- A colour and other optical properties that radiate heat back to the atmosphere;
- Providing resistance to flows of heat and moisture;
- Having an aesthetical appearance consistent with the building and the sounding environment;
- Serving functions such as building stability and fire-resistance.

8.4.2 Ventilation system

The increase of ventilation increases energy consumption for conditioning internal spaces of the building. Unwanted air leakage increases the need for more spaces cooling energy. Building codes specify a maximum allowed leakage, but detecting leaks can be difficult and expensive and compliance rates are often poor. The use of a proper ventilation system will reduce the need for air-conditioning such as the case of LCB4. There are different ways to reduce the energy losses through ventilation systems include the following:

- Reduce leaks in building envelope and ducts to minimize uncontrolled infiltration;
- Use natural ventilation where possible and at appropriate times of the year;
- Use efficient, variable speed motor fans to reduce the time required for air-conditioning;
- Use heat and moisture exchange devices.

8.4.3 Space Conditioning Equipment

The efficient design of building envelopes can dramatically reduce the cooling load; even so there will be a need for mechanical systems for conditioning the internal of the buildings. Fresh air from outside of the building is needed to improve the quality of the internal environment and to replace exhaust air, heat and moisture generated by occupants and building equipment. Air conditioning in buildings involves both cooling of the air and reduces its moisture. The traditional air-conditioning unit accomplishes both tasks using the principle of heat pumps. Single air-conditioning units are used in most residential buildings in Oman while most large commercial buildings use central chillers to cool water and transfer heat from water to air closer to the occupied spaces. The performance of building cooling systems can be enhanced by systems that store thermal energy. Thermal storage in buildings can be provided with different methodologies including the following:

- Designing buildings to store and remove thermal energy within their structure without affecting internal spaces;
- Using ice and other phase change materials.

Chillers are more efficient when outdoor air is coolest because chillers can store cooling capacity in a pre-cooling chilled water or ice during night hours when less energy is required to cool water, and then using it in the afternoon when more energy is required for cooling spaces. This can yield small site energy savings through chiller efficiency improvements during the cooler night-time hours. Also, shifting peak energy demand away from peak periods could improve electric utility operations by reducing the required generation capacity and, subsequently, reducing the need to build new electricity systems. Furthermore, from the monitoring of reference LCBs' energy consumption the building provided with a cool water chiller (LCB2) shows less energy requirements per square metre (Table 8.3).

Reference building	Spaces cooling load kW/m^2
LCB1	18.63 kW/m^2
LCB2	11.50 kW/m^2
LCB3	13.81 kW/m^2
LCB4	15.33 kW/m^2

Table 8.3: Reference LCBs' spaces cooling load in November 2014

8.4.4 Lighting

The key strategies for improving the efficiency and quality of lighting in buildings are lighting design, window and window shutters, sensors and lighting devices type. Good lighting design can ensure that light levels are adjusted to user requirements. In residential buildings, intense task lighting may be required for detailed working areas such as a kitchen while much lower levels can be used in common areas. Daylight is a major contributor to reduce a building's demand for artificial light. The following strategies can be used to provide natural lighting in interior spaces of buildings:

- Light reflectors that bring light from roof collectors into interior spaces;
- PV devices that are transparent to visible light and convert infrared and other portions of the sunlight into electricity;
- Combined systems that generate electricity in rooftop PV units and transmit visible light through fibre optic systems to interior spaces.

8.4.5 System-Level Opportunities

Lighting, windows, HVAC equipment, water heaters and other building equipment currently can be equipped with smart controllers or wireless communication devices. These systems provide many opportunities for improving building efficiency, managing peak loads and providing services valuable to control the cost of energy consumption of buildings. Low-cost sensors and controls also expand opportunities for individuals to achieve greater control of the thermal and lighting conditions. System level management can achieve the following energy reduction tasks:

- Control of building environment;
- Control major home appliances;
- Utilise weather forecasts to develop pre-cooling strategies;
- Adapt performance from utilities using rate structures to minimize overall energy usage.

However, such systems will require the local public to be aware of their advantages and working principle in order to operate a building in the optimal way.

8.5 Energy performances and renewable energy use

This research monitored five SOTA low carbon buildings in Oman which are provided with PV systems and solar hot water. Results revealed that three of these buildings were able to generate electricity from PV panels more than the amount they consumed over the course of a year. This shows the abundant renewable energy sources in the country that are currently not in use. Renewable energy use has been recognized globally to enhance innovate approaches or strategies for the mitigation of carbon dioxide emissions due to energy use related to the building construction and operation. Therefore, suffice to say that renewable energy such as solar and wind play a significant role in sustainable development. The expected ability of reference LCBs' PV systems shows that a half rooftop of PV panels in an Omani house will be able to produce on average more than 50% of its annual energy need (Table 8.4). However, the cost associated with energy tariff and RE technologies' initial prices are major barriers in Oman.

Reference building	Energy consumption	Potential PV system generation kWh/year	Generated RE as % of consumption
LCB1	30837	11243	37.5
LCB2	15343	22486	73
LCB3	38890	16724	43
LCB4	15768	22346	71

Table 8.4: Potential CBs' PV systems energy productions and consumptions.

8.6 Benchmarks of energy consumption

Applying benchmarking to building energy consumption serves as a strategy for measuring energy performance of a given building over time, as compared to other similar buildings or relative to modelled simulations of a reference building constructed to a particular standard. The conventional buildings reviewed by this research have average energy consumption of 274 kWh/m^2/y whereas monitored LCBs' energy consumption is found to be 110 kWh/m^2/y. This demonstrates the need to implement energy reduction technologies as used in these green building in the existing and future residential building in Oman. It has been mentioned in previous chapters that these buildings included cost-intensive technologies and materials, which raised their initial cost in such a way that they will not be able to repay this cost from energy saving. Hence, it is important to map energy efficiency techniques to cost benefits in order to provide environmental friendly homes that are acceptable to local markets. For energy benchmarking, this research suggests the energy benchmark for residential buildings in Oman to be between the average conventional building energy consumption and SOTA buildings' energy consumption, which is from 110 kWh/m^2/y to 274 kWh/m^2/y. Further, this value is broken down into levels to indicate grades of building efficiency (Figure 8.2). The proposed scheme is adapted from the Tunisian energy efficiency scheme (described in chapter two) with additional modifications. In this scheme, the energy efficiency of the building is ranked on a scale of nine classes according to three categories. Three scales are dedicated to each category based on percentage reduction achieved by the building compared to SOTA buildings' energy usage. The increments between these classes of efficiency set to be equal based on the deferent between energy consumption of SOTA buildings and average energy consumption of conventional buildings.

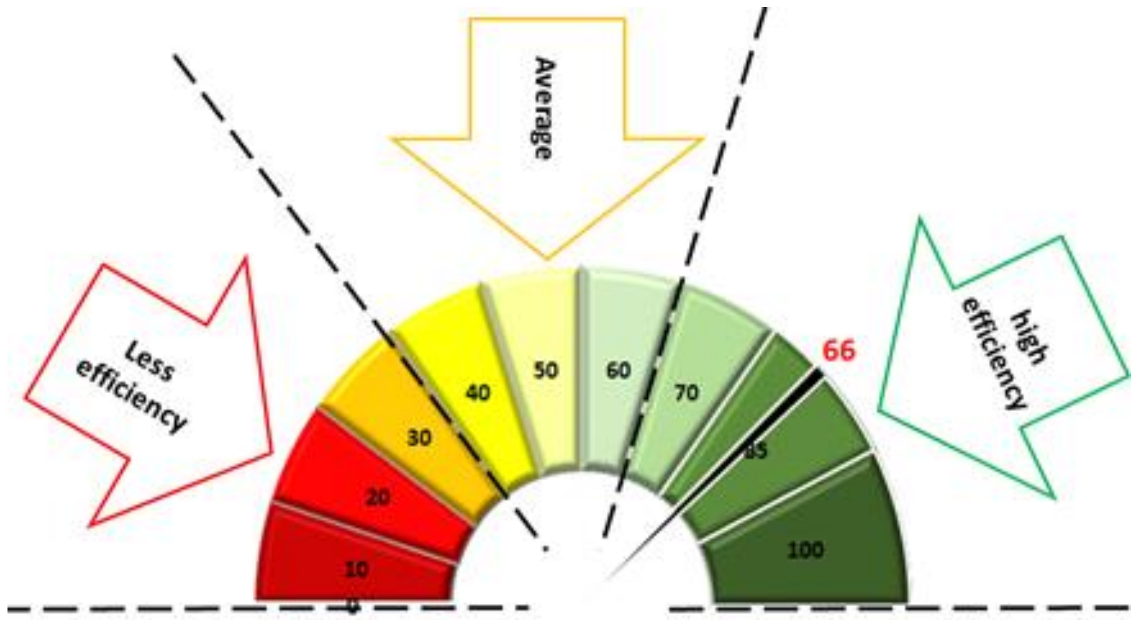


Figure 8.2: Suggested energy rating scheme

8.7 Cost of low carbon building

In general, high-efficiency building elements are more expensive than equivalent standard-efficiency elements. As shown in earlier chapters a main barrier to implementing low energy materials and technology was the high cost of these EEMs. Hence, a cost-optimal LCB needs to integrate EEMs into the construction of a building without high initial cost. Innovative design teams can incorporate simple, passive energy-efficiency strategies into the building architecture and envelope at no additional cost. Building orientation, massing and layout can be designed to reduce building thermal loads without increasing material or construction costs. Other passive strategies, including daylight redirection, thermal massing, natural ventilation and solar shading, can be integrated with the building structure to create architecturally pleasing designs that also save energy. Well integrated solutions can often eliminate the need for additional controls and mechanical components that increase first cost and require long-term maintenance. However, in the case of Oman, additional cost will be needed to integrate RE and implementing insulation to the envelope. Therefore, in this section the additional cost due to implementing these measures will be evaluated. Further, the ideal energy price will be suggested in order to determine the suitable price of energy that will lead to implementing these EEMs. In this regard, the cost-optimal calculations method, which approved by the EC Delegated Regulation, is used in the analysis (EU) No. 244/2012 of 16).

In this method, the first step is determining the cost-optimal solutions for low energy building measures and assessing different retrofit measures for the building envelope and implemented technology. Single-retrofit measures are combined into coherent combinations (or packages) of reduction measures. The application of each package creates a reduction scenario for the building energy consumption. Then, different reduction scenarios are tested, involving improvements in the building envelope and energy cost. For each reduction scenario, the renewable and non-renewable primary energy use is calculated, as well as the net present value (NPV) of the building cost (including investment costs, maintenance costs and energy-related costs) for the building's life cycle period. Regarding residential building in Oman, the life cycle of the building, current energy cost and cost of energy reduction measures are provided in table 8.5.

Parameter	Value
Current electricity price	0.015 OR, 0.0075 (£)
Current installation price of PV system per m^2	102 (£204)
CDD for Muscat	5140
Base temperature	25 °C
R Value for hollow concrete	0.32
R value for reinforced concrete	0.48 m^2K/W
Interest rate for Oman	0.01 to 0.05 assume 0.017

Table 8.5: The main parameters used in cost analysis of LCB

For evaluating energy saving due to insulation, the cooling degree day method, described in chapters five and six, is used to estimate the potential energy reduction per m^2 of the building envelope due to implementing insulation to the building wall. A study conducted in China concluded that using expanded polystyrene as an insulation material in a hot climate is more efficient than other types examined in that study; therefore, this type of insulation is considered in this chapter. Thermal conductivity and price of insulation material are the two vital factors that should be considered in selection of insulation thickness.

The principle made here is that the improvements of the building envelope's U value due to implementing insulation will reduce the amount of heat transferred to the internal of the building. Subsequently, this will reduce cooling load and energy requirements for thermal comfort. Then, this saving of energy is mapped to the current costs of electricity in order to obtain its viability (Table 8.6). The total cost saved from energy for cooling over the building's lifetime is converted to present value by using NPV function using a discount rate and a series of future payments over the whole life cycle of the building (Eq. 8.1).

$$\text{NPV} = \sum_{n=30}^{n=0} \frac{FV}{(1+i)^n} \quad \text{(Eq. 8.1)}$$

Where:

NPV is the present net value from saving energy due to application of insulation

FV is the annual future value of saving energy

i is the interest rate (in the case of Oman it is between 1.7 to 5%)

n is the number of years (in the analysis considered to be 30 years)

	Thickness of insulation (mm)			
	0	**10**	**25**	**50**
Cost m^2 (OR)	0	77.4	78.39	144
Cost m^2 (£)	0	51.6	52.26	96
Insulation R Value	-	0.69	0.69	0.69
Wall R Value	0.324	0.324	0.324	0.324
Overall R Value	0.324	0.693505	0.715244	0.751476
U Value	3.08642	1.44195	1.398124	1.330714
Annual cooling energy requirements per m^2	31.98	14.75	17.49	18.19
Annual energy saved kWh	0	235.9774	279.906	291.0819
Annual cost save (OR)	0	3.539661	4.198589	4.366229
(NPV) considering life cycle (30 years)	0	-21.46	-22.10	-43.81

Table 8.6: Analysis of cost benefits and thickness of insulation

Application of insulation in the construction of residential buildings is not a common practice in Oman; hence the costs used in this analysis are an average estimation made by local contractors during interview 3 (Alshukaili, 2016). Further, this analysis did not include inflation rate, which in Oman is projected to be around 3.67% in 2020, or other economical parameters (Oman Inflation Rate Forecast 2016-2020, 2017). However, these results can be trusted as a guide for analysing potential economical visibility of application insulation in the environment of construction of residential buildings.

On the other hand, implementing RE to the context of Omani dwellings will assist in reducing the amount of conventional energy required for residential buildings. The country has potential renewable energy resources, in particular wind and solar. In fact, all the GCC countries boast some of the highest solar irradiances in the world (EPIA, 2010; Al-Shalabi, Cottret and Menichetti, 2013). However, this will require investigating the potential visibility of implementation based on the current tariff of electricity. In reference to this, the potential energy production and cost associated with installation of RE in reference CBs analysed using the NPV method is based on data collected from reference LCBs, interviews and questionnaires.

The factors controlling energy production of PV systems include total solar panel area (m^2), solar panel efficiency (%), annual average solar radiation (W/m^2) and performance ratio (a coefficient for losses). The coefficient of losses ranged between 0.5 and 0.9, with default value of 0.75 for Oman, and refers to the losses accrued due to conversion of the energy from DC to AC power and to installation independently of the panel efficiency. These losses include the following (Alshukaili, 2016):

- Inverter losses (4% to 10 %)
- Temperature losses (5% to 20%)
- DC cables losses (1% to 3 %)
- AC cables losses (1% to 3 %)
- Shadings 0 % to 80% (specific to each site)
- Losses at weak radiation (3% to 7%)
- Losses due to dust, snow (2%)
- Other losses

The most efficient solar panels available on the market have efficiency rated as high as 25% (Beeri *et al.*, 2015), whereas the solar panels used in reference LCBs ranged from 14% to 16%. The lowest value is considered in this analysis, assuming 95% no shading on the system, and combining these parameters and factors in a mathematical expression, the following equation is generated to estimate potential energy production of a PV system for a residential building (Alshukaili, 2016):-

$$E = A \times r \times H \times PR \qquad \text{(Eq. 8.2)}$$

Where:-

E = Energy (kWh)

A = Total solar panel Area (m^2)

r = solar panel efficiency (%)

H = Annual average solar radiation (kWh/m^2)

PR = Coefficient for losses (assumed for Oman 0.75)

Further, the analysis assumed the following assumption and justification:

- Life cycle of PV system is 20 years based on the average life of PV panels 20 years, inventor 5 years and other components of the system 20 years;
- The analysed buildings are grid connected to feed any extra energy produced PV system to the utility grids, which means no energy production is wasted when the system generates more than it consumes;
- Inverters will be replaced four times during the whole system's life based on current cost of inventors projected to the future cost using NPV function;
- Each individual panel has an area of 1.3 - 1.7 m^2; based on this the usable roof area is calculated assuming 20% area will be required as pathway for services;
- The total cost of PV system is obtained from the average cost of LCBs' systems (from chapter five);
- Constant energy cost considered for generated and purchased at a rate of 0.015 OR (0.03 £).

	CB1	**CB2**	**CB3**	**CB4**
Total area	212	320	240	340
Usable roof area	100	150	110	150
Potential system size	36	72	54	72
System initial cost	9360	18720	14040	18720
Potential production	11243	22486	16724	22346
Annual energy consumption	30619	15139	38643	15539
Cost saving due to RE (OR)	168.645	337.29	250.86	335.19
NPV for 20 years	-8843.94	-15984.1	-12441.7	-16011.7

Table 8.7: Potential RE energy production and cost saving

The analysis for implementing insulation and RE to the construction of residential buildings in Oman revealed negative saving due to the current energy cost (Table 8.6, Table 8.7). This suggests the removal of subsidies from the electricity tariff or providing higher cost for electricity purchased from PV systems in order to make the consideration of these options more viable.

8.7.1 Benchmarking of cost payback

Cost has been a major barrier to the adoption of energy-efficient materials and technologies in buildings. Advances in designs and use of technologies can cut energy consumption associated with HVAC lighting and home appliances. A significant payback can be achieved through the selection of cost-effective, energy-efficient technology and materials. However, two major challenges in developing widely affordable LCBs in Oman include the high initial cost of materials and technologies and prices of energy.

The results from applying insulation to the envelope of residential buildings and implementing RE in Oman have demonstrated they are not beneficial options based on the current electricity prices. Thus, subsidies on electricity prices need to be removed or reduced in order to support the application of these energy efficiency measures (Table 8.8); (Figure 8.3).

Cost of Electricity kWh in (OR)	Cost of Electricity kWh in (£)	NPV in 30 years (OR)		
		10 mm	25 mm	50 mm
0.015	0.03	-21.4638	-22.0961	-43.805
0.02	0.04	-20.0184	-20.7514	-42.4067
0.025	0.05	-18.573	-19.4068	-41.0084
0.03	0.06	-17.1276	-18.0622	-39.61
0.035	0.07	-15.6822	-16.7175	-38.2117
0.04	0.08	-14.2368	-15.3729	-36.8134
0.045	0.09	-12.7915	-14.0283	-35.4151
0.05	0.1	-11.3461	-12.6836	-34.0167
0.055	0.11	-9.90066	-11.339	-32.6184
0.06	0.12	-8.45527	-9.99435	-31.2201
0.065	0.13	-7.00987	-8.64971	-29.8218
0.07	0.14	-5.56448	-7.30507	-28.4234
0.075	0.15	-4.11909	-5.96043	-27.0251
0.08	0.16	-2.67369	-4.6158	-25.6268
0.085	0.17	-1.2283	-3.27116	-24.2285
0.09	0.18	0.217098	-1.92652	-22.8301
0.095	0.19	1.662492	-0.58188	-21.4318
0.1	0.2	3.107886	0.762754	-20.0335

Table 8.8: Viability of implementing insulation and suggested energy cost

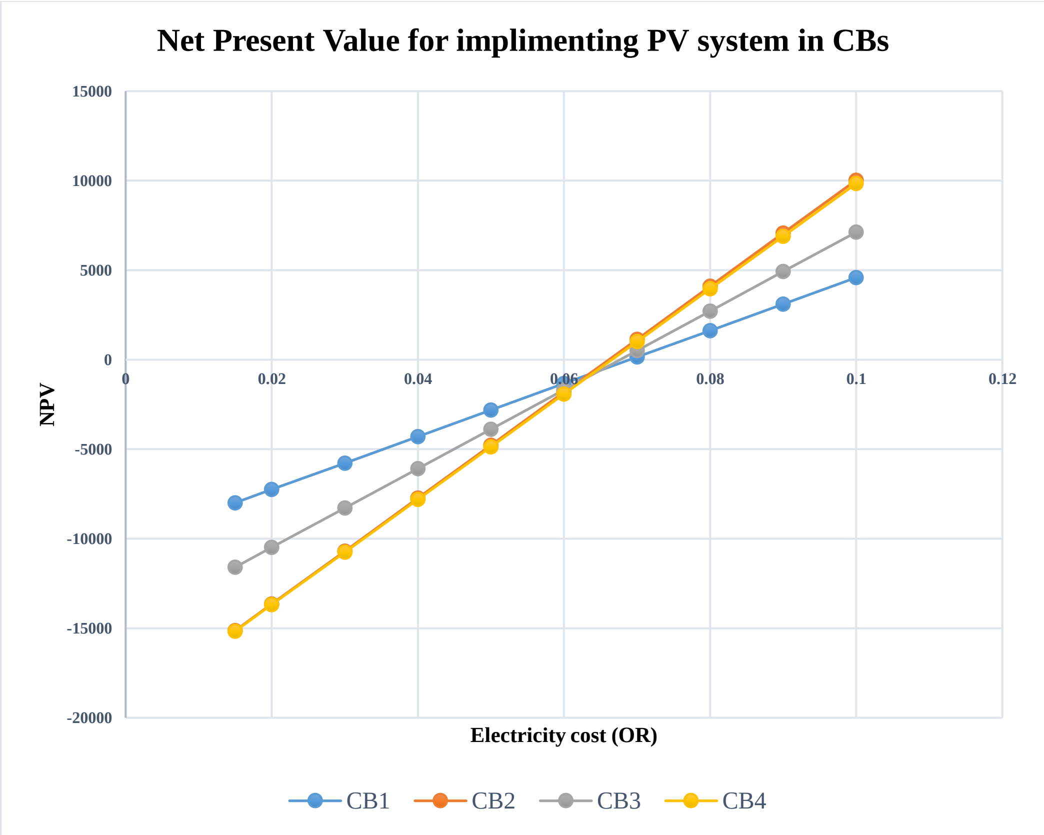


Figure 8.3: Viability of implementing RE and suggested energy cost

The viability study of these two options shows that the implementation of 10 and 25 mm insulation will result in better buyback than 50 mm. Further, the cost of installing PV systems in Oman is expensive compared to international cost because of limited available companies. However, results from the application of both EEMs is considered a viable option if the cost of electricity is adjusted to average world electricity price, i.e. UK prices.

8.8 Potential roadmap for residential LCB

Based on the analysis from this chapter and the previous chapters, the potential roadmap for adopting a residential LCB strategy for Oman comprises three main elements: target, plan and method, to achieve this target within an allocated period of time. These three elements need to be carefully drafted based on the economic, environmental and social conditions of the country. In most cases, governmental and nongovernmental bodies focus on one aspect of sustainability which creates a gap in implementing a whole strategy. Weakness in any pillar of sustainability will be directly reflected on the others. Therefore, a roadmap to residential LCB must consider all the components of the three pillars of sustainability.

Thereby, a roadmap to LCB includes details on setting a vision and a target and developing action plans. The main actors for the roadmap are government sectors, consultancy firms, contractors, building managers, capital project managers, as well as those involved in the delivery of residential buildings, major building retrofits, tenants and building occupants. In addition, an independent body is required to be responsible for managing and monitoring the application and outcome of the roadmap strategy. Hence, for Oman's constraint, the suggested roadmap is summarized in the following table.

Roadmap element	**Description**
Vision	Transformation of residential building and its industry chain to low carbon environment by reducing conventional energy consumption of Omani dwellings by 40% compared to its current level by 2030.
Targets areas	• TA_1 Types of residential building; • TA_2 Target energy performances of building; • TA_3 Building occupants' behaviours and energy usage; • TA_4 Home appliances; • TA_5 Industry capacity; • TA_6 Percentage RE from residential building; • TA_7 Cost efficiency of LCB; • TA_8 Research and development (R&D).
Action	• ACT_1 New buildings designed to a target performance; • ACT_2 Existing buildings have to be refurbished • ACT_3 Increase awareness of public • ACT_4 Create sustainable industry • ACT_5 Setting up of appropriate training schemes • ACT_7 Create labelling system for home appliances • ACT_8 Implement building energy scheme • ACT_9 Create green building code, energy efficiency building guide • ACT_{10} Introduce renewable market, lows and provide support • ACT_{11} Provide progress assessment and provide required update • ACT_{12} Support research programmes
Achievements	At the end of the period the country will have reduced energy consumption of residential buildings, established a low carbon society and industry, created a legislation framework and provided a suitable environment for future further energy reduction.

Table 8.9: Elements of roadmap for LCB transformation

8.8.1 Vision

Oman is vulnerable in terms of energy supply security compared with other GCC countries due to limited conventional energy sources. The proven production life of oil in Oman is between 16 and 32 years (Almulla, 2014). This requires the country to establish a goal to reduce the energy consumption of the residential buildings sector, the major energy consumer. Since achieving a paradigm shift in the building sector requires time, vision to achieve this goal has to be set within the time period of oil production life. Thus, the transforming period is suggested to be between 2030 and 2040; year 2030 (V2030) is selected as the target for a transformation period. The selection of target reduction has originated from the possibility of reducing current energy consumption by 3.7% to 18.2% without considerable additional cost, which has been proven in chapter six. Hence, the suggested value is less than average possible reduction value, therefore, it will be an achievable target. In line with V2030, strategic planning and targets are required to drive the residential building industry to turn to the energy efficiency business. This planning is required to ensure that the residential buildings sector and other built environment systems and stakeholders, over the maintained period of time, are in the right direction through the creation of the required organization and for governmental bodies to set up the required actions and follow up the progress.

8.8.2 Target Areas

The target area for this roadmap plan refers to the actors and stockholders of residential buildings and their role in order to achieve the main vision. Therefore, all residential buildings' stockholders are involved to participate according to their duties and responsibilities. The government is the main actor; hence it will be the main target that will be responsible for providing the required legislation framework and follow-up application and to encourage other parties to achieve their duties. Further, the government will be required to provide financial support for research programmes, initial subsidies on low carbon technologies and a training scheme on the application of new legislations.

8.8.3 Action

An energy policy roadmap cannot be represented by a single action or law. The policy consists of laws, regulations, and programmes, but their directions are under the influence of the strategic plan provided by government. The main actions required as per table 8.9 are:

- Discontinue construction of residential building by the current method, and include energy efficiency standards. Since the country has not yet devised such standards, it will be ideal to adopt standards from neighbouring countries, i.e., GCC or MENA countries. Furthermore:-
    - Create standards for green building;
    - Establish laws and regulations for renewable energy use;
- Create a framework to refurbish existing buildings in order to meet the requirement of the suggested standard;
- Increase public awareness by encouraging people to participate in events and programmes like Earth Day. Increase the energy efficiency culture by providing data on energy efficiency and CO_2 emissions on home products and make people responsible for energy efficiency in their own properties;
- Establishing appropriate continuous training schemes for industrial parties. All parties of the construction process are continuously provided with certified education and training schemes in order to meet the required specialised level for an energy-efficient buildings industry;
- Create or import an internationally recognized home appliances energy labelling system. The energy efficiency certificates must be displayed on all imported or locally manufactured home appliances. Further, other home equipment and service devices should be rated according to a suitable scheme. Also, inefficient lighting should not be used or accepted for the trade in the country;
- Establish research centres and potential collaborative work with international agencies.

8.9 Chapter summary

This chapter suggested a roadmap on how to implement best practice low carbon residential buildings in Oman based on the examined EEMs. Before that, it examined the visibility of implementing insulation and adoption of a PV system in Omani residential buildings based on the current electricity tariff, and then investigated the optimal electricity price which could lead to the adoption of these EEMs. Next, it identified the vision, and action required, and suggested an implementation pathway for the suggested roadmap. The research advocated a transition period up to 2030 to reduce energy consumption of residential buildings from conventional energy sources by 25% to 50% based on its current level. The action required to achieve this reduction comprises forming a legislation framework for efficient buildings, encouraging society and industry to adopt transformation to a low carbon environment and providing required funds and support.

9 Discussion

9.1 Introduction

This research aimed to investigate domestic building energy performance in order to devise a suitable reduction strategy. The context of the Sultanate of Oman was selected as a case study, being one of the top 20 countries in CO_2 emission per capita (List of countries by carbon dioxide emissions per capita, 2017). This work has demonstrated the use of experimentally validated evaluation of domestic building energy consumption using both quantitative monitored data and qualitative data obtained from the design and construction team, utility company, occupants and building users. This enabled a more holistic analysis of factors and systems that have contributed to the minimal adoption of residential LCB in Oman, and subsequently the high energy consumption in this sector.

Consequently, this chapter explores the strengths and weaknesses of the application of the findings of this research in the context of Oman. It discusses lessons learnt from the studied buildings in relation to their limitations and design, and the economic, social and environmental aspects that must be considered when evaluating domestic building energy consumption.

The research was subjected to limitations regarding time, data collection and cost of technologies and materials used in the reference LCBs. However, despite these limitations the study has addressed the main hypothesis and embraced the potential opportunities for low carbon building solutions if the building stakeholders considered the issues of design and size, deployment of building elements, daylight and shading, cooling strategies, construction practice, home appliances, landscape, occupants' lifestyle and social impacts. Finally, this chapter illustrates the potential CO_2 reduction from residential buildings in Oman when using R-BEET and also the interdependencies of the main parameters that control energy usage in the residential buildings sector.

9.2 Limitations

Although the research has covered its goal to devise a possible LCB strategy for Oman, the first of its kind in the country, there were some limitations. One of the limitations of this work was the sample size of the case study buildings. This was due to the limited time, logistic support and cost associated with an increasing number of sample buildings. A larger sample in research terms tends to increase the certainty of its results and reduce the potential for errors. However, the results obtained illustrate confidence of acceptance based on the analysis undertaken in the previous chapters.

Another important limitation of this study was the limited availability of data and references for the case study country. This is because it is the first time the country has been subject to such a study so most data was collected from primary sources.

The real cost of materials and technologies used in LCBs was difficult to obtain as some of these materials were not available in the local market or were donated by local and international companies. The research adopted cost evaluation by local contractors for whom such materials were new.

Despite the energy performance achieved by the reference LCBs, the study did not examine the ethical impact of this type of building on society or preferences regarding design, materials and even the shape; for example, LCB2 is cylindrical in shape which is not usual for residential buildings in Oman.

The estimation of conventional buildings' energy use was conservative for many reasons. For example, it did not address opportunities for reductions in miscellaneous electric loads that contribute to building energy consumption. It was not possible to collect directly measured readings for home tasks' energy consumption due to social factors; therefore an energy audit and estimation were adopted, that gave trusted results, as shown in chapters four and five, but are still conservative.

Moreover, the analysis did not place a value on the increased amenities associated with an energy efficiency measure, or on the ability of these measures to provide valuable services to utility companies. It was also highly likely that currently unknown innovations would lead to further cost reductions and performance improvements.

The energy template, Residential Building Energy Efficiency Template (R-BEET), was designed for residential buildings only, however, its concept can be extended to create different versions to cover other types of building, such as a Commercial Building Energy Efficiency Template (C-BEET), etc.

Finally, although the energy template created in this research showed its capability to be used for evaluating residential building based on the selected reference buildings from Muscat, it was not validated for a larger number of buildings or for sample buildings from outside Muscat. Furthermore, it was limited to the social, economic and environmental norms of Oman. Thus, its application in different regions would require modifications, the main one being the weather file used, that is currently limited to Muscat only. Therefore, if it is approved for use in the whole of Oman, other main cities' weather files will need to be uploaded. Also, the template did not include a heating load because Muscat has no heating degree days.

9.3 Low carbon houses opportunities

According to the concept of sustainability, natural resources should be used in a way to secure them for future generations. The majority of decisions in the building design process are taken at the early design stage. This means that buildings should be designed and operated during their life cycle in a manner of less consumed energy. The design phase presents the greatest opportunity to obtain high-performance buildings, but pertinent performance information is needed for designers to be able to tackle multidisciplinary and contrasting objectives. This opportunity can be provided by considering the use of R-BEET as an energy tool calculator for selecting the optimal design.

In addition, it is recommended to use low-energy rated home appliances to ensure maximum conservation of energy in the building. In this regard, R-BEET will be beneficial as a building energy management tool to predict energy usage for different home tasks, zones and times, etc.

9.3.1 Design

One of the most effective strategies for reducing domestic energy consumption is to optimally design the building envelope to reduce heat gain, that leads to excessive energy consumption for cooling. A high-performance dwelling envelope can increase the occupants' comfort and well-being while reducing energy requirements for cooling and lighting. It has been proven in this thesis that the building envelope is a major factor in determining the amount of energy needed for cooling and lighting. Designing a dwelling with non-integrated EEMs clearly leads to negative results.

9.3.2 Optimum orientation

It was noted that the current Omani dwellings omitted the proper orientation of the building in the absence of architectural design criteria and building codes. The findings of this research therefore indicated the need for a major update of the construction standards and building codes and their enforcement in the construction industry in Oman. These codes are required to observe the basic issues of optimal orientation for energy performance in dwellings. In the extremely hot climate of Oman the northern orientation of windows typically results in cooler indoor conditions due to minimisation of incident solar radiation. The majority of conventional buildings included in this study appear to be badly oriented or designed without attention to wind direction, solar radiation or other environmental conditions.

It was evident from the results of the investigated dwellings in this study that the orientation of the building was one of the factors affecting the dwelling's energy consumption. Research demonstrated that the orientation of a building could increase its energy consumption by about 5%. Therefore, appropriate orientation of buildings for improved energy performance is a costless energy reduction measure.

9.3.3 Glazing ratio, size and orientation

Glazing size and orientation are considered to be key issues when considering building energy consumption in most climatic impacted orientation of the building. Traditionally, in hot weather countries, area of windows are limited and small in size in order to reduce the impact of the external climate on indoor spaces and reduce glare. However, most contemporary dwellings in Oman appear to be designed with large single glazed windows without any attention given to heat gain from them. Fenestration should be carefully integrated into building facades considering the amount of heat they will allow to enter into the internal spaces of dwellings. In the geographical location of Oman, it is recommended to provide maximum openings along the northern façade and avoid or reduce openings on the eastern and western façades. This concept allows maximum daylight and minimum heat gain from windows. It appears, to some extent, in this study that the designers of the studied CBs have not carefully considered sizes and location of windows. It has been found, in some cases, that windows were placed in every possible facade of the building. Moreover, the type of windows is a major factor in energy consumption of buildings. Indeed, multilayer glazing with low emissivity can lead to further reduction in energy consumption.

9.3.4 Daylight and shading

A good façade design provides fenestration and shading that can address the problem of glare and reduce the impact of high heat gain while providing visual privacy for the occupants. Also, in a hot climate, shading devices on fenestration are required to keep sunlight out during summer days but allow it to enter in winter. However, this study found that the conventional case study dwellings were not provided with external shading devices.

Daylight as a natural source of light provides satisfactory illumination that reduces the need for artificial lighting. Nevertheless, due to the extremely hot external environmental conditions, daylight has to be well managed over the course of the year against heat gains and to avoid glare.

It has been found that shading that controls the surrounding environment is able to reduce the temperature of air entering the building, that also contributes to the building's energy performance. It is important to permanently shade all walls and windows to exclude heat gain from accessing the building. Considering the case of LCB4, described in chapter five, shading the whole dwelling was able to reduce air temperate by 6.1 ^{o}C (Figure 9.1). This design strategy is not practised in Oman and other GCC countries because of minimal attention paid to such solutions by architects and local industry (HamoudShabab, 2014).

Figure 9.1: Entire the building shading.

9.3.5 Cooling and ventilation strategies

Mechanical cooling units that improve indoor environmental conditions are required in Omani dwellings due to the extreme hot climate. Today, most Omani people construct or buy their houses without air-conditioning units and then retrofit a mechanical cooling system. In most cases these systems are purchased based solely on cost, without considering unit efficiency. Energy consumed in houses for thermal comfort in Oman is generally high, therefore cooling devices' efficiency will play a major role in the overall energy consumption. Although an efficient AC system is expensive to install, the results from this study assumed that the inefficiency of AC systems' plays a role in the incremental reduction of the cooling load and thus its energy cost. It is very clear from the literature review and energy audit that the design of contemporary homes in Oman is increasingly relying on air-conditioning to control the indoor environment over the whole year. Hence, there is an urgent need for efficient cooling and ventilation strategies in dwellings including non-energy based methods. The design, therefore, should consider passive cooling options, where available, and select efficient mechanical cooling systems. As air conditioning is commonly used to create comfortable conditions, the number of operating hours required to achieve thermal comfort can be substantially reduced by careful design of homes. It is essential to combine different techniques of ventilation (stack, as used when dumping heat behind a suspended ceiling, or cross-ventilation for cooling of occupants), and the installation of fans is also recommended to reduce the operating period for the AC in certain months. The use of fans as an adaptive approach can create a comfortable environment when the temperature and relative humidity levels are within acceptable ranges, and consequently would reduce cooling energy consumption.

9.3.6 Construction practice

The construction of contemporary residential buildings in the Sultanate of Oman is classified as a concrete based industry. Concrete blocks, floor tiles and precast concrete are common products employed in the construction of dwellings. Building envelopes are mostly constructed from concrete brick walls of 220 mm thickness, with high thermal conductivity. The envelope system needs to have a high thermal capacity to provide sufficient time-lag in order to keep the internal environment cool during the daytime. Moreover, providing external walls with insulation would considerably reduce heat gain through the envelope, however, this option has never been practised in residential buildings in Oman. It appears that Oman's residential buildings have a poor thermal resistance envelope that increases heat transfer across walls leading to poor energy performance of dwellings. All CBs reviewed in this study were found to have an external wall thickness of less than 250 mm, whereas all LCBs have an external wall thickness of 350 to 600 mm, including insulation. Furthermore, all interviewed contractors revealed they had not constructed any residential buildings that included additional thermal insulation (AlBalushi, 2015). Insulating buildings is essential in extremely hot conditions to exclude the harshness of that climate from the internal environment of the house. However, in a hot climate with high humidity the insulation material could be damaged by condensation, that increases the potential of excess dust mite populations and the concentrations of mould spores. Therefore, it is recommended to choose materials that resist damage from condensation. Furthermore, it is argued that walls with high thermal mass can store coolness, and potentially have less problems from dew-point than lightweight insulated walls (Ruivo, Ferreira and Vaz, 2013).

9.3.7 Home appliances

As mentioned in the previous chapters, energy efficiency is not a top priority for Omani's when buying appliances, where little attention is paid to energy labelling. It is recommended for low-energy homes to choose highly energy efficient appliances or upgrade the system when it reaches the end of its life span. New home appliances offer better energy savings compared to old technology, such as TVs.

In addition to appliance efficiency, another aspect worth further consideration is that the standby consumption of certain types of domestic appliance is becoming an increasing problem with the escalation of their density in homes. These are items that occupants do not tend to think to turn off, but gradually their numbers in homes accrue and consume a great amount of electricity over the year. Now there are several solutions to reduce standby electricity consumption, such as standby savers that turn off appliances from standby status.

9.3.8 Landscaping and building envelope shading devices

The discussion in the earlier section of this chapter suggests it is important to consider the shading of the whole building to manage solar access. Furthermore, it is important to lower the ground temperature surrounding the house to reduce the local air temperature, and therefore it is recommended to increase vegetation and plants around the dwelling (Figure 9.2). It is well known in geographical locations such as Oman that the highest rate of heat gain passes through the roof so shading the whole building or use of a green roof could substantially reduce the overall heat gain of the building's envelope. It is evident that all five LCBs have some sort of shading on the roof or on the walls. The commonly used shading strategy on the roof was placing PV system panels on the roof to provide some sort of shading. Therefore, it is important to spread the experience of these SOTA examples in order to encourage the local market in creating optimum solutions.

Figure 9.2: Shading by surrounding trees and vegetation on walls (LCB5)

9.3.9 Occupant lifestyle

The energy consumption of a building is the result of its occupancy, therefore the occupants' lifestyle affects their energy requirements at home. This makes occupancy behaviour one of the most significant drivers of the dwelling's energy efficiency and performance. Recently, several studies have confirmed the impact of the users' behaviour on a building's energy consumption and conservation (Yu *et al.*, 2011). Therefore, along with the good design of a dwelling, the occupants' lifestyle should also correspond for an ideal high-performance dwelling.

Education on how to manage building energy is essential to reduce overall energy consumption of buildings with low thermal performance. Further, providing the occupants with a home manual on how to use the building efficiently, and data sheets on all types of home appliances installed or expected to be installed will assist users regarding energy conservation at home.

9.3.10 Social impact

The actual impact of a building's energy depends on how it is used by the occupants, the quality of home goods and many other human-related factors. Therefore, a building must be designed for the possible understanding of users' needs and their ability to interact with its technologies for better energy performance. Human decision and associated social and behavioural aspects impact either positively or negatively on a building's energy. For example, energy subsidies, whereby efficiency investments lower the cost of energy services, encourage wasteful behaviour. The removal of such subsidies would contribute to equipment and interface designs and forecasting. How we use energy determines the amount of CO_2 emissions to the environment; hence, to control this problem and ensure a conducive outcome we should mitigate the low-carbon strategies.

9.4 Template application

Currently, tools and energy calculators for evaluation impact of energy consumption of buildings on the environment are highly required. R-BEET is designed for Oman, and opens opportunities to predict and evaluate residential building energy consumption using a simple and low-cost method. This makes it possible to evaluate significant samples of different building design concepts for implementing a low carbon strategy. The adoption of a LCB strategy in Oman faces significant constraints including predicting the potential benefits; hence, R-BEET could work as an applicable assessment and analytical tool to support an energy saving option, and subsequently potential social, economic and environmental benefits of its application.

9.4.1 Economic impact of integrating LCB practice in Oman

The results of the current study demonstrate it is possible to determine minor energy efficiency improvements without a need for direct increase of construction cost. These improvements come from design consideration and energy management. For example, orientation and using shading devices could achieve such reduction. According to results from parametric modelling, proper orientation of building could reduce its energy consumption by up to 5% and a green roof and water pond surrounding a house can reduce ambient temperature by 6.1 ^{o}C. These reductions will have a positive impact on the energy cost over the life cycle of a building. For example, considering the 5% annual energy consumption reduction, if the average Omani house energy usage is 24757 kWh/year (from chapter three), this reduction will equal 1238 kWh/year, which equates to 18.57 OR (£37.14) per year based on current subsided energy. If the 67% subsidies are removed from electricity prices, and considering the current international price of fuel used to generate electricity, then this value in 50 years, the life cycle of building, will equate to 5,018.92 OR (£10,037.84).

However, for further energy savings and reduced use of conventional energy sources, additional strategies will be required. These strategies involve considering high-performance materials, additional thermal insulation, high performance glazing, more efficient domestic appliances and adopting RE sources. These solutions are considered financially non-viable options based on the current energy cost and ability of local industries. Therefore, a grant rate, in the form of energy efficiency subsidies, may be needed as a strategy to encourage building owners and industry to apply these solutions. The energy efficiency subsidies should only apply to buildings that fulfil the prescribed minimum energy efficiency level – for instance, based on the energy rating scheme described in chapter eight. In order to motivate further integrated energy retrofits, the level of grant support should be differentiated to encourage deep, low-energy retrofits, particularly those that reach the energy efficiency level similar to SOTA LCBs.

The use of R-BEET would be valuable here to evaluate energy consumption scenarios to determine percentage reduction. This action is reasonable to ensure that the best possible energy efficiency level is installed and practised. This could be applied to any building, not only for new dwellings, but also it can be extended to existing buildings. The analysis from chapter eight shows that for an integrated energy efficiency policy, the target efficiency should be identified in order to provide the required support. Furthermore, on-site renewable energy production can be added to this scheme for an improved energy efficiency target.

9.4.2 Environmental impact

Global warming and climate change are the recognized global environmental crises that will have tremendous impacts on human existence on the earth. These issues result from emissions of GHG generated from industrial activities and anthropogenic activities including use of energy in residential buildings. Therefore, a low-energy performance building is a beneficial solution to the environment. Improved building systems and improved building envelopes reduce the need for mechanical cooling and heating equipment; thus it suffices to say that buildings with dramatically reduced energy use are in most cases more advantageous to our environment than conventional designs.

A high-performance envelope reduces the cooling and heating loads that must be satisfied by the mechanical system and also permits alternative systems that are characterized by low-energy use to meeting the reduced loads. The use of R-BEET to design and evaluate low-carbon building has the potential to result in more energy efficient buildings, that will also lead to greater environmental benefits. In addition, carbon mitigation strategies have co-benefits for development such as the development of the renewable energy industry and reduced use of conventional energy sources. The cost mitigating low-carbon strategies is low because consumers can save what they could have spent on conventional fossil-fuel based energy.

9.4.3 Carbon footprint reduction

With increasing concerns about global warming and climate change, it is imperative for world governments to impose effective policy instruments to promote energy saving and reduce carbon emissions. Johansson (2006) theoretically evaluated the policy instruments used to contribute to the reduction of CO_2 emissions while preserving the competitiveness of the construction industry. In the Oman context, this research suggested implementing energy reduction measures described and analysed in previous chapters via a roadmap explained in chapter eight based on using R-BEET.

Appropriate to this research, energy consumption of residential buildings is quantified by overall energy usage, home task activities and related energy consumption issues. The International Energy Agency reported (2010) the generation of 1 kWh of electricity in Oman produces 794 grams of CO_2 emission. So, if the template was used in the design of reference CBs, this could lead to 5% energy consumption less than the current status due to orientation alone. Accordingly, this research quantified CO_2 emissions due to the operating of reference CBs and possible reduction (Table 9.1) (Appendix F). The energy and its associated CO_2 reduction illustrated in this table does not consider electricity losses due to transportation.

Ref. Building	**kWh/y**	**Performance Index kWh/m^2**	**CO_2 Emissions (kg)**	**Emissions in kg/m^2**	**CO_2 / capita (kg)/ year**	**Reduction due to use of R_BEET**	**CO_2 reduction Kg/ year**
Building 1	30619	144.4292	24311.49	114.6768	4051.9	1531	1215.59
Building 2	15139	76.07538	12020.37	60.40385	2404.1	757	601
Building 3	38643	161.0125	30682.54	127.8439	4383.2	1923	1534.13
Building 4	15539	70.63182	12337.97	56.08166	1370.9	777	616.90

Table 9.1: Possible energy reduction due to usage of R-BEET

The Paris Agreement, which dealt with GHG emissions mitigation, adaptation and finance, projected for starting in the year 2020, stated that each country determines, plans and regularly reports its own contribution that should be made in order to mitigate global warming. There was no mechanism to force a country to set a specific target by a specific date, but each target should go beyond previously set targets. Each country's contributions should be reported every five years and are to be registered by the United Nations Framework Convention on Climate Change (UNFCCC) Secretariat (Paris Agreement, 2015). Oman signed the agreement on 22 April 2016 but still has not mentioned the date of deposit of instruments of ratification or accession nor a date when the agreement enters into force.

Inspecting Oman's CO_2 emission status, according to the World Bank, the latest record in 2012 was 16.49 tonnes/capita/year compared to the world average of 4.99 tonnes/capita/year (Figure

9.3) (CO2 emissions (kt) | Data, 2017). Based on the trend in this chart, the emissions are subjected to greater increase, even faster than the increase of GDP and the population which are the main two drivers for calculating countries' emissions. Oman has not yet set a target year to start reducing its CO_2 emissions; taking such action requires investigation of the possible targeted sectors to reduce overall emissions. Hence, the building sector in Oman is one of the most appropriate targeted industries due to its potential possibility for emissions reduction. This means that the amount of CO_2 the sector emits can be decreased more effectively and at less cost than is the case for other sectors.

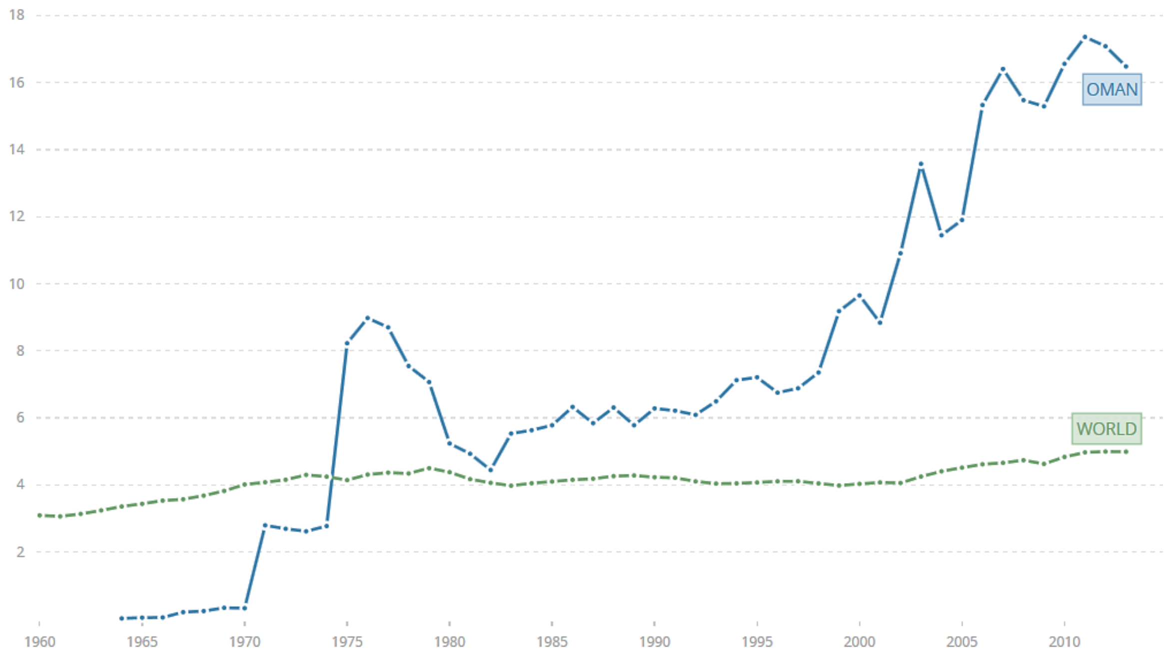


Figure 9.3: Oman and world average CO_2 emissions tones per capita

(Source: World Bank)

Considering the results from Table 9.1, the latest available data on annual energy consumption of residential buildings in Oman, which is 10039.48 GW/h, the possible reduction of CO_2 is expected to be 398567 tons per year.

Hence, it can be argued confidently that the application of the roadmap strategy for shifting residential building to a low carbon option, described in chapter eight, using the designed building energy template will lead to considerable emissions reduction.

9.5 Interdependencies

The design guideline framework, described in chapter seven, seeks to evaluate some of the lifecycle EEMs identified in this research. Nevertheless, it omits evaluating performance risk; hence, this discussion attempts to describe the factors that could be incorporated within this framework to increase understanding of performance risk, which will lead to more realistic expectations. The present research has shown that the potential reduction of the energy consumption of residential buildings by adopting LCB strategies, which have been employed in the SOTA, is enormous. The results of this study are beneficial to different groups and parties that are related to the building industry in general and residential building in particular.

However, building energy consumption is related to several interdependent factors. These include all building stakeholders and the surrounding environmental conditions. Yet, none of them is capable of optimizing the efficiency of different energy strategies in an ideal scenario without considering the effects of other factors. The main factors included in this discussion are related to design and operation, cost, environmental and social constraints.

The collected data contained a great deal of variability, as shown in the analysis of energy consumption, and illustrated a clear view of the building's operating patterns. Further, this variability indicated the existence of the difference between the theoretical design models of buildings and the practical reality of buildings in operation. Therefore, the design and in-use operation of buildings are interrelated.

If the construction industry were to move towards the adoption of prescribed energy targets for dwellings there would be a strong dependency for the building sector on performance predictions. There are, however, significant factors affecting energy efficient application that are difficult to predict related to future energy cost and occupant lifestyle as well as government plans and intentions. Current designers and building operators alike may be unaware of the expected future changes of consumption and operating patterns. In this regard, probabilistic predictions that produce a likely range of energy consumption data may be helpful to evaluate the impact of such changes.

The climatic conditions and future projected scenarios will have a great impact on the building design and its operational energy. This, as previously mentioned in several sections of this research, will require the current designed and constructed buildings to be able to serve their function in the future. The issue of future-proofing buildings has an impact on the current construction methodology and its associated costs. Moreover, it will influence living styles and building operation, which tends to impact on occupants' social life.

Finally, the social factor is the main factor in building energy consumption, as the consumed energy reflects occupants' life style, income and behaviour, etc. Nevertheless, the ability of the construction industry alongside environmental conditions and the other factors discussed here are interdependent on the social and other factors. For example, the industry's willingness to adopt a certain building designs is subject to the acceptance of society for this type of building, while the willingness of people to adjust their life style to suit a certain building design depends on cost of the building and its operation.

9.6 Chapter Summary

In conclusion, this chapter has discussed the research outcome and summarised its limitation and the impact of the application of its outcome. The research has successfully covered the topic of adopting LCB strategies for the case of the Sultanate of Oman. However, it was subjected to limitations due to time, data collected, and acceptance of the designed building. Despite these limitations, the results from this research are acceptable as it has covered the main hypothesis. In addition, the discussions revealed that the opportunities for low carbon building are possible if the building stakeholders considered this issue in the design of building and size, allocation of building elements, daylight and shading, cooling strategies, construction practice, home appliances, landscape, occupants' lifestyle and social impacts. Moreover, it has illustrated the possibility of CO_2 reduction from residential building in Oman using R-BEET. Finally, it discussed the interdependency of the main factors of the residential sector where it has been found they are strongly interdependent on each other.

10 Conclusion

10.1 Introduction

This thesis sought to explore the suitable passive and renewable low carbon strategies for residential building in the hot, humid climates considering the Oman environment as a case study country. Driven by the shortage of experimental validated studies in the Gulf, this mixed method assessment study was dedicated to the investigation of available SOTA LCBs in Oman in order to examine the applications of EEMs in the context of the case study country.

The conclusions that follow provide an outline of the most significant contributions to the topic: *"PASSIVE AND RENEWABLE LOW CARBON STRATEGIES FOR RESIDENTIAL BUILDINGS IN HOT HUMID CLIMATES"*. It summarises the key outcomes of the research in relation to the objectives outlined in chapter one, discusses their significant contributions to the body of knowledge, the limitations of the research undertaken, and, identifies areas for further investigation.

In conclusion, this research established that a significant reduction (up to 58%) in total energy consumption of residential buildings could be achieved by adopting passive and renewable strategies. In addition, efficient energy reduction could be expected when implementing energy efficiency measures using the energy template R-BEET. Such reductions of total energy consumption of residential building could also be achieved without adding to the initial building cost. Moreover, implementing EEMs could lead to further reduction of energy usage. However, the absence of a national plan for implementing an energy conservation strategy leads to less adoption of these measures. Furthermore, it has been found that the current construction regulations, practice and materials do not support the energy conservation of buildings. Moreover, the local society is not contributing to the issue of energy conservation in buildings. Hence, the findings of this thesis recommend the development of a policy for passive and renewable energy strategies for residential building including energy regulations for buildings.

10.2 Research Outcomes

The main research outcome is that this study has successfully achieved its aims and objectives. This study validated the viability of adopting low carbon building in domestic buildings in Oman. The study has suggested reducing the energy consumption of residential building by implementing passive and renewable strategies in order to solve the problem of excessive fossil fuel consumption in Oman. Thus, the applicability of this proposal was examined in the environment of Oman as a pathway to shift the residential building sector towards low carbon building alternatives.

10.2.1 Objectives fulfilled

The research objectives have been fulfilled as follows:

I. **Review the regulatory and energy context of state of the art (SOTA) practice of low carbon domestic building and construction in Oman:** The status of low carbon building has been reviewed in chapter two at four levels; international level, MENA region level, GCC countries level and Oman. It was found that Oman falls behind in the current construction practice of low energy domestic buildings. This been caused by obstacles and challenges facing the development of sustainable housing in Oman. The housing sector in Oman has transformed from a traditional local society into new and advanced housing units, prompted by the use of modern architectural construction methods and design without considering the subsequent energy performance of these buildings in the hot humid environment of Oman. This has resulted from the absence of strategy and codes for low carbon building, leading to less adoption of low carbon buildings. The chapter concluded that the country should establish passive and renewable energy strategies to overcome this situation. Furthermore, a clear research methodology was required to investigate the possible strategies.

II. **Establish research methodology suitable for the research topic**: The study addressed the world-view of the research, and methodologies adopted in this field of the research. The mixed method research approach from both qualitative and quantitative aspects was used, and the selected research methods provided suitable procedures for achieving each objective, alongside a detailed approach to collect and analyse data. The methodology adopted was based on the assumption that designing strategies for low carbon residential buildings in the hot and humid climate of the

Sultanate of Oman is capable of bridging the gap that exists in the energy consumption of residential buildings.

III. **Determine the energy consumption profile and key elements of operational deficiency that increase energy consumption of residential buildings in Oman**: The research determined domestic building annual energy profiles and identified the significant causal factors resulting in performance discrepancies, and their origins in the buildings' life cycle. This research found that the factors leading to the non-adoption of low-carbon buildings in the Sultanate of Oman were correlated to the culture of the local society, the absence of any government intervention or support, the poor construction ability of the local construction industry and marketing difficulties due to higher initial costs, making the construction sector unwilling to consider this type of construction.

IV. **Determine building energy system boundaries, needs and requirements:** The research identified key building energy system elements and the main factors that contributed to excessive energy consumption, and then estimated building energy needs to inform energy performance targets. Furthermore, the key attributes of low carbon buildings for a hot and humid climate were identified through pilot case study houses, where the energy consumption for various home tasks were evaluated. In addition, the research established a building energy system and the boundaries of residential buildings for energy benchmarking, analysed the building energy sub-systems and parameters controlling demands, reviewed the building energy reduction measures for low carbon strategies, analysed the building energy profile for the energy diagnostic and strategy application through a case study and, finally, summarised the key attributes for low carbon building guideline design for a hot and humid climate.

V. **Develop design guideline framework for LCB based on Energy Efficiency Measures (EEMs) for a hot climate:** The study examined Energy Efficiency Measures (EEMs) used in SOTA LCBs in a hot, humid climate using a case study approach for the whole building energy system to develop an energy efficiency guideline framework. The analysis has shown potential energy consumption reduction in domestic building of 67% based on the consideration of these measures. Consequently, the results suggested that it was important to establish a residential building energy template (energy calculator) to act as tool for developers, architects and civil engineers to design low energy homes in Oman that meet local requirements and overcome environmental challenges.

VI. **Devise a LCB template to evaluate options of residential LCB in Oman considering; Energy requirements, Building operation, Home appliances:** A low carbon building energy template was devised to evaluate different options of residential building in Oman based on performance targets, usage profile and building characteristics. The template generates an energy consumption report for the monthly and annual consumption of a building based on user data input. The application of this template shows its potential use as a building energy calculator or as a rating tool for implementing energy strategy.

VII. **Map a suitable LCB strategy for Oman using the criteria of the template**: Based on the benefits of the EEMs' application a roadmap was devised for a strategy best suited to Oman's criteria and constraints. This strategy was designed based on identification of the planned goal (vision) and required actions, and suggested an implementation pathway for the suggested roadmap.

10.2.2 Contribution

Finally, based on the achievement of research objectives, this work has contributed to the body of knowledge as follows:

I. **Identified the current status of** LCB construction, practice and regulation in Oman compared to international level, MENA countries and GCC countries.

II. **The identification of local domestic building energy profile:** the research has generated a more comprehensive description of the energy consumption profile, thermal comfort and its relation with the energy consumed in dwellings, with an exploration of the physical design of the home and occupants' behaviour.

III. **Created climate specific design criteria:** a device design criteria framework for low carbon building in a hot, humid climate based on validated EEMs.

IV. **Benchmarking:** benchmarked the energy consumption of residential buildings in the selected case study country.

V. **Devised a new predicting tool:** a climate specific building energy template was developed to evaluate residential building energy – the Residential Building Energy Efficiency Tool (R-BEET).

VI. **Market value:** to date, cost benefits' evaluation of low carbon building options in the selected research case study country.

VII. **Roadmap for implementing energy conservation policy:** requirements and recommendations to adopt low carbon residential buildings in Oman.

In addition to energy consumption data, the monitoring system has produced a large volume of environmental data including solar radiation, wind direction and speed, and internal and external temperature and humidity for each of the monitored reference buildings. A detailed analysis of this data is beyond the scope of the present research but presents a great opportunity for future research. A performance evaluation of a recently constructed LCBs was undertaken to construct a detailed case study. The evaluation identified specific technical deficiency at the whole building level and at sub-system level influenced by physical design and occupants' behaviour. It has reviewed the influential factors causing high energy consumption in existing domestic buildings in the selected case study country.

10.2.3 LCB energy efficiency measures for hot climates

The results of this research demonstrate that simple strategies can be effectively implemented to reduce domestic buildings' energy demand in Oman. The implementation of key EEMs can substantially benefit the energy performance of a building. This research validated the potential energy reduction due to implementing EEMs in residential buildings in in Oman.

EEMs	Potential % energy reduction
Roof insulation	17.9 – 18.2
Use of High performance concrete	16.4 – 17.7
Wall insulation	12.9 – 13.7
Orientation	5.5 – 5.9
Shading	3.7 – 4.6

Table 10.1: EEMs potential reduction of energy

Nevertheless, in the case of Oman the research established there are barriers preventing the application of some of these EEMs, including:

- **Environmental constraints:** Including current weather conditions and the impact of climate change on energy use of future buildings.

- **Social and cultural:** Including the existence of social and cultural habits that limit the application of energy strategies.
- **Limited awareness of energy saving:** Including the absence of public participation.
- **Economic barriers:** Such as lack of available LCB technologies, funding or financing difficulties and limited support.
- **Limited government and technical drivers:** Including the absence of rules, regulations and guidance documentation, limited policy framework and strategic planning, funding or financing difficulties and limited action to exploit renewable energy sources.

However, some EEMs can be applied at less cost or without any extra cost or technical skills, but they will require actions from building industry stakeholders (table 10.1).

EEMs	Actions
Building shape and size (EEM1)	Minimise areas exposed to the sun compared to the size of the building; use WWR that is able to provide required daylight and ventilation without increasing the overall U value of the building shell
Orientation (EEM2)	Orientate the building to the north to reduce solar gain
Shading (EEM6)	Provide shading on windows or utilise the available shading objects
Natural ventilation (EEM7)	Optimise natural ventilation when weather conditions and environmental characteristics of the building permit
Daylight (EEM8)	Use natural light sources while minimising solar heat gain through use of shading devices and light shelves

Table 10.2: Lower cost EEMs

Thus, the required action should be considering building energy performance from the early stages of design. In this context, it is important to emphasise the role of the main building stakeholders including government bodies, architects and buildings' owners. The role of the government is introducing the required legislative framework; architects and industry need to consider different building design and materials; and finally, building owners are required to take responsibility for this issue.

These EEMs are not limited to Oman, they are common to any country located in hot, humid climates. However, they are more applicable to the whole MENA region, especially the GCC countries which share similar social and economic conditions with Oman.

10.3 Recommendations

The research offers a framework for the base design of domestic LCBs in the hot, humid climates of the Gulf in general and in the Oman context in particular. On the basis of the findings of this study, recommendations can be classified into three categories, for the different groups of stakeholders involved: decision makers, architect and consultants, construction market and contractors and owners. The recommendations are made to suit both future and existing domestic buildings in Oman, and to meet the requirement to achieve high energy performance:

I. Recommendations for the decision makers:-

i. Provide a country-specific master energy plan that includes energy codes, regulations, market values of green construction, grants and support systems;

ii. Energy efficiency building codes in Oman should be established considering the impact of microclimates around domestic buildings, to ensure that the design of high-performance homes, considers the solar orientation of the building as well as the orientation, ratio of the fenestration within the façade, building materials, use of renewables and the efficiency of home appliances;

iii. Revise and update the approval conditions for new housing permits, adding energy consumption analysis to the design requirements;

iv. Revise and upgrade the planning regulations for new developments in Oman considering the solar orientation of the plots as a way to reduce the residential energy consumption;

v. Raise public awareness regarding the level of energy consumption in the home, and educate the public on the importance of reducing energy consumption to benefit individual household budgets;

vi. Introduce energy efficacy design measures in the construction of new government and community buildings in order to show the community the potential energy consumption reduction in buildings;

vii. Establish an energy market, including feed-in tariffs;

viii. Provide financial support for implementing energy reduction measures in new and refurbished buildings instead of providing subsidies based on energy cost;

ix. Establish an energy rating scheme for buildings to support the market value of low energy buildings;

x. Enforce the real estate developer to provide the energy consumption status of buildings.

II. Recommendations for architects and contractors

i. Provide a guide to encourage the clients commissioning the home at the early decision making stages to inform the appropriate choices that result in the designing of high-performance dwellings for both thermal comfort and reduced future energy consumption;

ii. Consider the use of building energy modelling tools in order to support design options that potentially consume less energy;

iii. A north-south orientation should be considered for the location of all habitable rooms in the home schematic design, regardless of the direction of the street. Also, consider the adopting low cost energy efficient solutions;

iv. Ensure that during the construction stages efficient, high resistance insulation in the whole building envelope, including roof, walls, floors and all openings, are specified to prevent unwanted heat gains from the outdoor environment.

v. Use efficient insulated low-E coated glazing or double, maybe triple glazing to minimise any unwanted direct solar radiation entering the home.

vi. The window-wall ratio should be reduced as much as possible, for an example should not more than those in reference buildings (15% to 22%);

vii. Design effective external shading devices and use landscaping to cool the surrounding environment to assist in the reduction of energy consumed for air conditioning systems;

viii. Living zones that are mostly occupied during the day should not be exposed to the harshest west facing part of a home. Recommend locating buffer spaces around living areas to limit the outdoor heat coming into these spaces;

ix. Provide energy modelling and analysis for the client in order to show the potential energy reduction and subsequently building operation cost reductions;

x. Remain up-to-date with the latest available technologies and materials in the field of energy efficient materials.

III. Recommendations for clients and consumers

i. It is strongly suggested to consult professionals at the early decision making stages of the design process instead of defaulting to cheap products or relying on the construction contractor;

ii. It is beneficial for existing low carbon dwellings to be retrofitted to meet the suggested guidelines as much as possible, in order to reduce electricity use.

iii. Setting the AC system thermostat at a higher temperature would help to reduce the cooling load on the dwelling and thus the lifespan of the cooling system.

iv. It is advisable to attempt to change the daily lifestyle in favour of less cooling demand to reduce energy consumption.

v. Consider the energy efficiency of newly purchased home appliances and devices as this will contribute to the overall energy bill of the house.

10.4 Potential future research areas

This research investigated energy consumption of residential buildings for the purposes of devising a country's strategy to shift the residential building sector to more low carbon options. However, the energy consumption of dwellings is a critical issue and the technical viability of low energy building strategies to meet the target energy performance in Oman requires further research. Therefore, this research suggests four different main areas of parallel research, namely: i) optimal architectural design of buildings in a hot, humid climate , ii) the influence of occupants' factors on building energy performance, iii) low carbon materials for hot, humid climates, and iv) optimal cost of low carbon building. The presented work is merely a step on the road towards low energy buildings in Oman. Much more work remains to be done in the area of energy standards and performance evaluation. The findings of the current work can provide the future research with various areas to investigate:

- The need exists to explore building energy use for different house design styles, volumes and surface areas, enabling architects and designers to make informed decisions on the impact that alterations in the design will have on the overall energy consumption. Further, the design criteria devised in chapter five will require further investigation to validate their application.

- The occupancy factors that influence the efficiency of building performance is not investigated in depth in this study. Occupants' effect on energy usage differs based on when the optimum environment is achieved not everyone is satisfied. Moreover, a sensitivity analysis of the internal heat gains (people, light, equipment) in the hot environment needs more consideration.
- With respect to the construction, the effectiveness of different construction materials for both the structure and insulation can be examined, as heat capacity and thermal conductivity change from material to material under different environmental conditions.
- Subsidising energy, especially electricity, for residential buildings seemed an intractable policy for many countries, especially those of the GCC. It was seen as part of the social contract between the citizens and the governments. However, shifting these subsidies to support energy policy needs more investigation in order to provide the suitable mechanism for a paradigm shift towards a low carbon environment at low cost.

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Appendix A: Residential building energy audit

Residential Building Energy Audit

Buiding 1	Built area:	212.5	Total occup	6	Location: Muscat

Rooms	Appliances	Rated Power (W)	Number in use	Use / day (hrs)	Daily Energy AC (Wh)
Sitting room	light	33	2	6	396
	TV	70	1	6	420
	DVD	-	-	-	
	Satellite receiver	36	1	6	216
	AC	1900	1	6	11400
					0
					0
					0
living room	light	40	2	17	1360
	computer	75	1	3	225
	printer	-	-	-	
	study light	-	-	-	
	iron	1200	1	1	1200
	heater	-			
	AC	1900	1	10	19000
bedroom 1	light	30	2	5	300
	computer	75	1	2	150
	printer	-	-	-	
	study light	-	-	-	
	iron	-	-	-	
	AC	1600	1	7	11200
bedroom1	light	30	2	7	420
	computer	-	-	-	
	printer	-	-	-	
	study light	-	-	-	
	iron	-	-	-	
	AC	1600	1	8	12800
bedroom1	light	30	2	5	300
	computer	-	-	-	
	printer	-	-	-	
	study light	-	-	-	
	iron	-	-	-	
	AC	1600	1	8	12800
bedroom1	light	-	-	-	
	computer	-	-	-	
	printer	-	-	-	
	study light	-	-	-	
	iron	-	-	-	
	AC	-	-	-	
Sub total					12800

Rooms	Appliances	Rated Power (W)	Number in use	Use / day (hrs)	Daily Energy AC (Wh)
bathroom	light	7	1	5	35
	hair drier	-	-	-	
	shaver	-	-	-	
	existing fan	12	1	24	288
	water heater	1100	1	3	3300
bathroom	light	7	1	2	14
	hair drier	-	-	-	
	shaver	5	1	0.25	1.25
	existing fan	12	1	24	288
	water heater	1100	1	3	3300
bathroom	light	7	1	2	14
	hair drier	-	-	-	
	shaver	-	-	-	
	existing fan	12	1	24	288
	water heater	1100	1	3	3300
bathroom	light	-			
	hair drier	-			
	shaver	-			
	existing fan	-			
	water heater	-			
bathroom	light	-			
	hair drier	-			
	shaver	-			
	existing fan	-			
	water heater				
bathroom	light	-			
	hair drier	-			
	shaver	-			
	existing fan	-			
	water heater	-			
		-			
Kitchen	light	60	2	7	840
	refrigerator	210	2	12	5040
	microwave	1270	1	0.1	127
	kettle	2000	1	0.1	200
	mixture	400	1	0.1	40
	freezer	260	1	12	3120
	existing fan	12	1	24	288
	water heater	1100	1	3	3300
	Elc. Coocker	-	-		
courtyard					
Washing area	washmachine	500	1	0.428571	214.2857143
	draier	-			
Garage (car park)	light	-			
	fan	-			
Others					
corridor	light	3	2	20	120
Sub total					24117.53571
Daily Total					36917.53571
Montholy					36917.53571

Summary

Appliances	total number	total hours use	power
lighting			3799
H Elec.			1011
HAVAC			67200
hot water			13200
washmachine			214.2857

Residential Building Energy Audit

Buiding 2	Built area: 199	Total occupants 5	Location:MUSCAT

Rooms	Appliances	Rated Power (W)	Number in use	Use / day (hrs)	Daily Energy AC (Wh)
Sitting room	light	60	2	7	840
	TV	85	1	7	595
	DVD	-	-	-	
	Satellite receiver	32	1	7	224
	AC	2570	1	7	17990
living room	light	60	2	12	1440
	computer	-			
	printer	-	-	-	
	study light	-	-	-	
	iron	1600	1	0.2	320
	heater	-	-	-	
	AC	2570	1	7	17990
	iron	-	-	-	
bedroom 1	light	60	2	7	840
	computer	-	-	-	
	printer	-	-	-	
	study light	-	-	-	
	iron	-	-	-	
	AC	2570	1	8	20560
bedroom1	light	60	2	4	480
	computer	-	-		
	printer	-	-	-	
	study light	-	-	-	
	iron	-	-	-	
	AC	2570	1	7	17990
bedroom1	light	60	2	12	1440
	computer	-	-	-	
	printer	-	-	-	
	study light	-	-	-	
	iron	-	-	-	
	AC	2570	1	8	20560
	TV	170	1	5	850
	Satellite receiver	35	1	5	175
bedroom1	light				
	computer				
	printer				
	study light				
	iron				
	AC				
Sub Total					102294

Rooms	Appliances	Rated Power (W)	Number in use	Use / day (hrs)	Daily Energy AC (Wh)
bathroom	light	30	1	3	90
	hair drier	-	-	-	
	shaver	14	1	0.1	1.4
	existing fan	12	1	4	48
	water heater	1200	1	3	3600
bathroom	light	30	1	3	90
	hair drier	-	-	-	
	shaver	-	-	-	
	existing fan	12	1	3	36
	water heater	1200	1	3	3600
bathroom	light	30	1	4	120
	hair drier	-	-	-	
	shaver	-	-	-	
	existing fan	12	1	8	96
	water heater	1200	1	3	3600
bathroom	light				
	hair drier				
	shaver				
	existing fan				
	water heater				
bathroom	light				
	hair drier				
	shaver				
	existing fan				
	water heater				
bathroom	light				
	hair drier				
	shaver				
	existing fan				
	water heater				
Kitchen	light	60	2	6	720
	refrigerator	320	2	12	7680
	microwave	200	1	0.4	80
	kettle	-	-	-	
	mixture	550	1	0.1	55
	freezer	-	-	-	
	existing fan	12	1	24	288
	water heater	-	-	-	
	Elc. Coocker	-	-	-	
	AC	3700	1	7	25900
courtyard	light	60	4	10	2400
Washing area	washmachine	500	1	0.5714286	285.7143
	draier				
Garage (car park)	light	-	-	-	
	fan	-	-	-	
Others					
corridor	light	30	1	12	360
Sub Total					48690.11
Daily consumption					150984.1
Monthly consumption					4529.523

Summary

Appliances	total number	tal hours u	power
lighting			7380
H Elec.			1249
HAVAC			103000
hot water			10800
washmachine			285.71429

Residential Building Energy Audit

Buiding type:	Built area: 240	Total occup: 9	Location:AL AMERAT

Rooms	Appliances	Rated Power (W)	Number in use	Use / day (hrs)	Daily Energy AC (Wh)	
Sitting room	light	40	2	10	800	
	TV	75	1	12	900	Sharp
	DVD	32	1			
	Satellite receiver	20	1	12	240	7-max
	AC	2405	1	9	21645	LG
living room	light	60	2	17	2040	
	computer	-	-	-		
	printer	-	-	-		
	study light	-	-	-		
	iron	-				
	heater					HOTX
	AC	2405	1	12	28860	ndos Tosh
bedroom 1	light	66	2	11	1452	
	computer	-	-	-		
	printer	-	-	-		
	study light	-	-	-		
	iron	-	-	-		
	AC	2405	1	9	21645	Vindows L(
bedroom1	light	66	2	5	660	
	computer	-	-	-		
	printer	-	-	-		
	study light	-	-	-		
	iron	0				
	AC	1800	1	8	14400	indows sha
bedroom1	light	66	2	9	1188	
	computer	-	-	-		
	printer					
	study light					
	iron					
	AC	2100	1	8	16800	ndows tosh
bedroom1	light	66	2	9	1188	
	computer	-	-	-		
	printer	-	-	-		
	study light	-	-	-		
	iron	1400		1		
	AC	2405	1	8	19240	
Sub Total					131058	

Rooms	Appliances	Rated Power (W)	Number in use	Use / day (hrs)	Daily Energy AC (Wh)	
bathroom	light	33	1	18	594	
	hair drier	-	-	-		
	shaver	-	-	-		
	existing fan	12	1	24	288	
	water heater	1200	1	3	3600	hotx
bathroom	light	33	1	16	528	
	hair drier	-	-	-		
	shaver	-	-	-		
	existing fan	12	1	24	288	
	water heater	-	-	-		
bathroom	light	33	1	18	594	
	hair drier	-	-	-		
	shaver	-	-	-		
	existing fan	12	1	24	288	
	water heater	1200	1	3	3600	hotx
bathroom	light	33	1	16	528	
	hair drier	-	-	-		
	shaver	-	-	-		
	existing fan	-	-	-		
	water heater	1200	1	3	3600	hotx
bathroom	light					
	hair drier					
	shaver					
	existing fan					
	water heater					
bathroom	light					
	hair drier					
	shaver					
	existing fan					
	water heater					
Kitchen	light	66	2	18	2376	
	refrigerator	LG	1	24		LG
	microwave	600	1	0.5	300	
	kettle	-	-	-		
	mixture	350	1	0.25	87.5	
	freezer	700	1	24	16800	
	existing fan	12	1	24	288	
	water heater	1200	1	7	8400	hotx
	Elc. Coocker	400	1	1	400	prollix 270
courtyard	light	264	8	10	21120	
Washing area	washmachine	450	1	3	1350	
	draier					
Garage (car park)	light	33	1	4	132	
	fan	-	-	-		
Others						
corridor	light	132	4	20	10560	
Sub Total					75721.5	
Total					206779.5	
Monthly in kWh					6203.385	

Appliances	total number	otal hours us	power
lighting			20792
H Elec.			1140
HAVAC			103350
hot water			15600
washmachine			1350

Residential Building Energy Audit

Buiding type:		Built area:	220	Total occupants	7	Location:AL MABILAH

Rooms	Appliances	Rated Power (W)	Number in use	Use / day (hrs)	Daily Energy AC (Wh)	
Sitting room	light	30	4	7	840	
	TV	65	1	7	455	sumsung
	DVD	-	-	-		
	Satellite receiver		-	-		
	AC	2340	-	7		classic
living room	light	60	2	18	2160	
	computer	-	-	-		
	printer	-	-	-		
	study light	-	-	-		
	iron	-	-	-		
	heater	-	-			dolphy
	AC	1800	1	8	14400	sharp
	iron	-	-	-		
bedroom 1	light	30	1	4	120	
	computer	-	-	-		
	printer	-	-	-		
	study light	-	-	-		
	iron	1350	1	1	1350	
	AC	2460	1	7	17220	General
bedroom 1	light	30	2	5	300	
	computer	-	-			
	printer	-	-	-		
	study light	-	-	-		
	iron	-	-	-		
	AC	2200	1	7	15400	ASSET
bedroom 1	light	30	2	4	240	
	computer	-	-	-		
	printer	-	-	-		
	study light	-	-	-		
	iron	-	-	-		
	AC	2570	1	7	17990	Sumsung
bedroom 1	light					
	computer					
	printer					
	study light					
	iron					
	AC					
Sub Total					70475	

Rooms	Appliances	Rated Power (W)	Number in use	Use / day (hrs)	Daily Energy AC (Wh)	
bathroom	light	30	1	3	90	
	hair drier	-	-	-		
	shaver	-	-	-		
	existing fan	12	1	3	36	
	water heater		1	3		dolphy
bathroom	light	30	1	6	180	
	hair drier	-	-	-		
	shaver	-	-	-		
	existing fan	12	1	24	288	
	water heater	1500	1	3	4500	dolphy
bathroom	light	30	1	6	180	
	hair drier	-	-	-		
	shaver	-	-	-		
	existing fan	-	-	-		
	water heater	1500	1	3	4500	dolphy
bathroom	light	30	1	6	180	
	hair drier	-	-	-		
	shaver	-	-	-		
	existing fan	12	1	24	288	
	water heater	1200	1	5	6000	hotex
bathroom	light					
	hair drier					
	shaver					
	existing fan					
	water heater					
bathroom	light	-	-	-		
	hair drier	-	-	-		
	shaver	-	-	-		
	existing fan	-	-	-		
	water heater	-	-	-		
Kitchen	light	60	2	8	960	
	refrigerator	120	1	12	1440	c4care
	microwave	800	1	1	800	sharap
	kettle	-	-	-		
	mixture					
	freezer	180	1	12	2160	hair
	existing fan	12	1	8	96	
	water heater	1500	1	10	15000	dolphy
	Elc. Coocker	-	-	-		
courtyard		30	1	13	390	
Washing area	washmachine	500	1	0.5	250	
	draier					
Garage (car park)	light					
	fan					
Others						
corridor	light	-	-			
Sub Total					37338	
Total					107813	
Monthly in kWh					3234.39	

Appliances	total number	otal hours us	power
lighting			5070
H Elec.			455
HAVAC			65010
hot water			24000
washmachine			250

Appendix B: CBs annual electricity consumption

OIFC

Oman Investment & Finance Co. (SAOG)

Statement of Accounts for Consumers

Date 26/10/2014 Page No 1 Of 1

Account — [redacted] -5 [redacted]
Meter No —
Geo — 2101
Route — 21010039000
Tariff — DOMESTIC (D)
Status — Active
OIFC Customer Code — MEW Acno —

Tr	Document Number	Document Date	Bill Month	Current Reading	Consumption	Tot. Days	A	M C	Debit	Credit	Bank	Balance
	Opening Bal. as on	01/01/14							19.920			19.920
RS	540002097919012 014	19/01/14								-19.920	601	0.000
BS	201401067563	01/02/14	0114	305510	1468	31		1	14.755			14.755
BS	201402108820	01/03/14	0214	306696	1186	28		1	11.920			26.675
RS	540002097931032 014	31/03/14								-26.675	601	0.000
BS	201403002470	01/04/14	0314	307925	1229	27		1	12.355			12.355
RS	540002101613042 014	13/04/14								-12.355	602	0.000
BS	201404131312	01/05/14	0414	310158	2233	30		1	22.445			22.445
RS	540002097914052 014	14/05/14								-22.445	601	0.000
BS	201405171781	01/06/14	0514	313969	3811	32		1	42.590			42.590
RS	550125091418062 014	18/06/14								-42.590	602	0.000
BS	201406329907	01/07/14	0614	318474	4505	32		1	53.630			53.630
BS	201407327984	01/08/14	0714	322850	4376	30		1	51.655			105.285
BS	201408220861	01/09/14	0814	326469	3619	32		1	39.680			144.965
RS	550125091421092 014	21/09/14								-144.965	602	0.000
BS	201409206920	01/10/14	0914	330207	3738	32		1	41.485			41.485

Nov 13 1935
Dec.13 1472

OIFC

Oman Investment & Finance Co. (SAOG)

Statement of Accounts for Consumers

Date 26/10/2014 | Page No 1 Of 1

Account — [redacted] -7
Meter No —
Geo — 2702
Route —
Tariff — DOMESTIC (D)
Status — Active
OIFC Customer Code —

MEW Acno — NA

[redacted]

Tr	Document Number	Document Date	Bill Month	Current Reading	Consumption	Tot. Days	A	M C	Debit	Credit	Bank	Balance
	Opening Bal. as on	01/01/14							62.430			62.430
BS	201401254428	01/02/14	0114	6552	341	28		1	3.430			65.860
RS	BATCH-BPM	02/02/14								-10.000	11	55.860
RS	BATCH-BPM	25/02/14								-35.000	11	20.860
BS	201402163569	01/03/14	0214	6905	353	27		1	3.550			24.410
BS	201403113435	01/04/14	0314	7598	693	28		1	6.965			31.375
RS	BATCH-BPM	23/04/14								-31.000	11	0.375
BS	201404077432	01/05/14	0414	8672	1074	28		1	10.795			11.170
RS	BATCH-BPM	22/05/14								-12.000	11	-0.830
BS	201405260865	01/06/14	0514	10284	1612	32		1	16.205			15.375
BS	201406262030	01/07/14	0614	12747	2463	32		1	24.755			40.130
BS	201407436004	01/08/14	0714	15545	2798	32		1	28.260			68.390
RS	EPAYMENT-EHC	22/08/14								-50.000	610	18.390
BS	201408332169	01/09/14	0814	17678	2133	32		1	21.440			39.830
BS	201409320640	01/10/14	0914	19607	1929	32		1	19.390			59.220
RS	BATCH-BPM	22/10/14								-20.000	11	39.220

Nov. 13 725
Dec. 13 677

OIFC

Oman Investment & Finance Co. (SAOG)

Statement of Accounts for Consumers

Date 26/10/2014 | Page No 1 Of 1

Account — [redacted] -5
Meter No —
Geo — 2613
Route —
Tariff — DOMESTIC (D)
Status — Active
OIFC Customer Code — MEW Acno —

[redacted]

Tr	Document Number	Document Date	Bill Month	Current Reading	Consumption	Tot. Days	A	MC	Debit	Credit	Bank	Balance
	Opening Bal. as on	01/01/14							222.951			222.951
BS	201401376179	01/02/14	0114	15648	1515	32		1	15.230			238.181
RS	BATCH-CASHIER240	26/02/14								-100.000	6144	138.181
BS	201402375754	01/03/14	0214	17364	1716	31		1	17.250			155.431
BS	201403427948	01/04/14	0314	19542	2178	25		1	21.890			177.321
RS	BATCH-BPM	23/04/14								-155.000	11	22.321
BS	201404412269	01/05/14	0414	22958	3416	32		1	36.605			58.926
BS	201405308849	01/06/14	0514	28686	5728	32		1	76.055			134.981
BS	201406425553	01/07/14	0614	34913	6227	31		1	86.235			221.216
RS	BATCH-BPM	02/07/14								-50.000	11	171.216
BS	201407311178	01/08/14	0714	38914	4001	31	Y	1	45.465			216.681
BS	201408426302	01/09/14	0814	49074	14161	61		2	208.110			424.791
CB	PREAVGBILL_CAN	01/09/14								-45.015		379.776
CT	PREAVGBILL_CAN	01/09/14								-0.450		379.326
RS	BATCH-BPM	06/09/14								-50.000	11	329.326
BS	201409176331	01/10/14	0914	53994	4920	29		1	59.980			389.306

Nov. 13 = 1801
Dec. 13 = 1634

* Difference →

OIFC

Oman Investment & Finance Co. (SAOG)

Statement of Accounts for Consumers

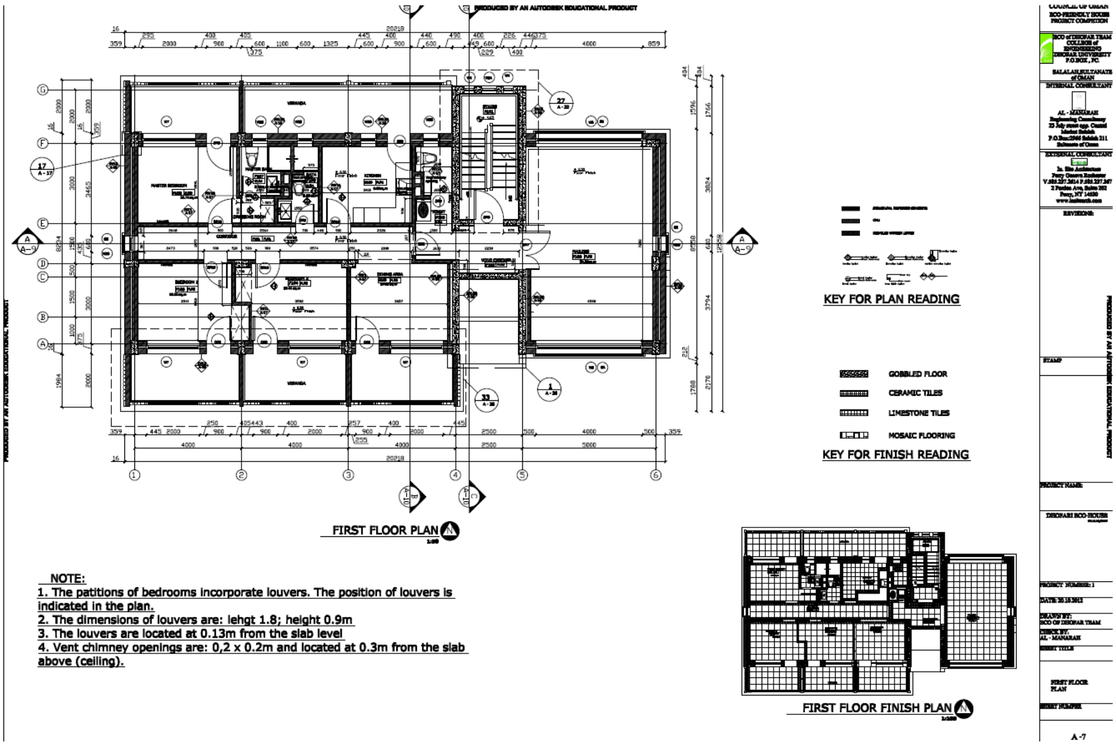
Date 26/10/2014 Page No 1 Of 1

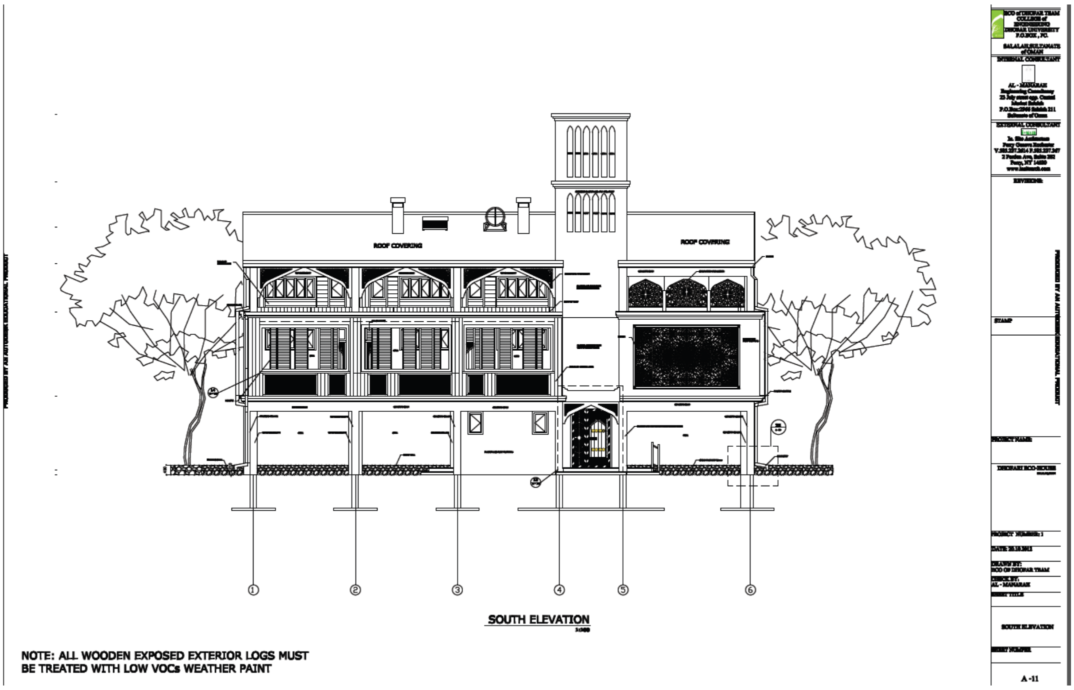
Account — [redacted] -7 [redacted]
Meter No —
Geo — 2472
Route — 24720280000
Tariff — DOMESTIC (D)
Status — Active
OIFC Customer Code — MEW Acno —

Tr	Document Number	Document Date	Bill Month	Current Reading	Consumption	Tot. Days	A	M C	Debit	Credit	Bank	Balance
	Opening Bal. as on	01/01/14							100.930			100.930
BS	201401148908	01/02/14	0114	198797	901	31		1	9.055			109.985
BS	201402075855	01/03/14	0214	199856	1059	28		1	10.645			120.630
RS	BATCH-BPM	03/03/14								-40.000	11	80.630
BS	201403214528	01/04/14	0314	200786	930	28		1	9.350			89.980
BS	201404392735	01/05/14	0414	201823	1037	32		1	10.425			100.405
BS	201405344794	01/06/14	0514	202989	1166	31		1	11.720			112.125
BS	201406132690	01/07/14	0614	204575	1586	31		1	15.940			128.065
BS	201407035212	01/08/14	0714	205804	1229	31	Y	1	12.355			140.420
CT	PREAVGBILL_CAN	01/09/14								-0.065		140.355
CB	PREAVGBILL_CAN	01/09/14								-12.290		128.065
BS	201408034568	01/09/14	0814	207943	3368	53		2	33.850			161.915
BS	201409087512	01/10/14	0914	209246	1303	28		1	13.095			175.010
RS	EPAYMENT-EHC	12/10/14								-20.000	610	155.010

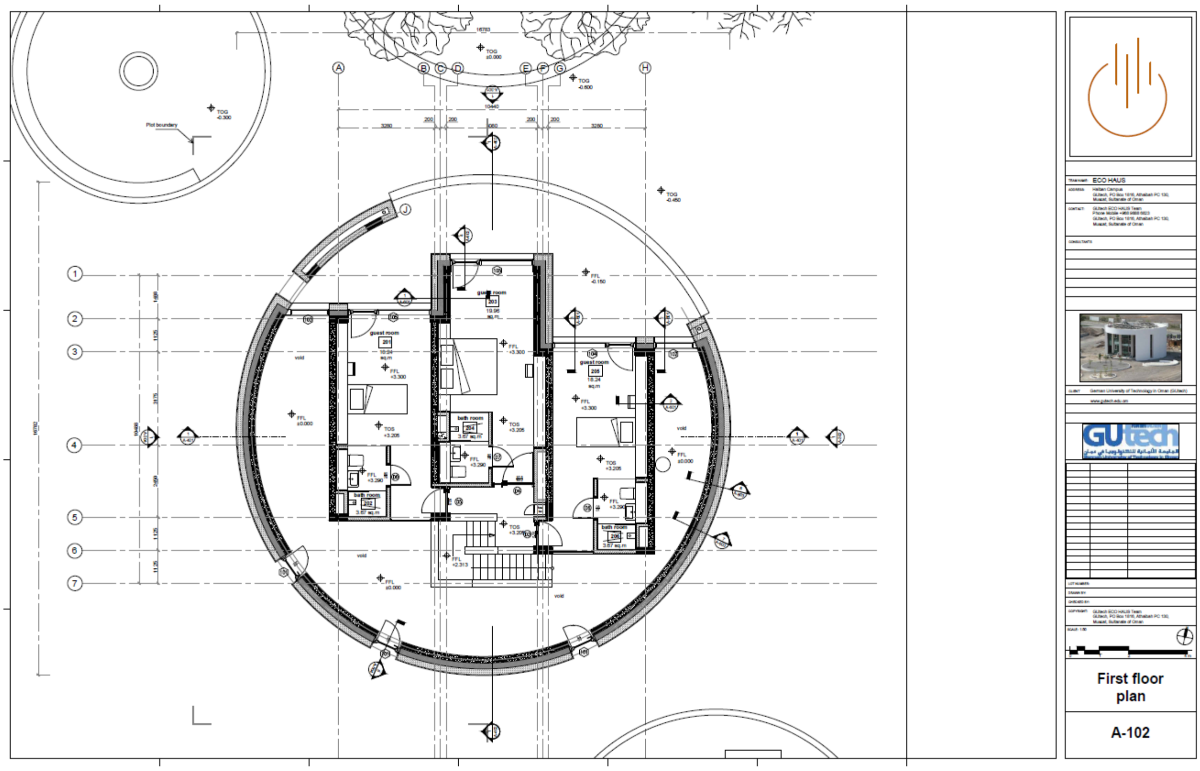
Nov. 13 1143
Dec. 13 935

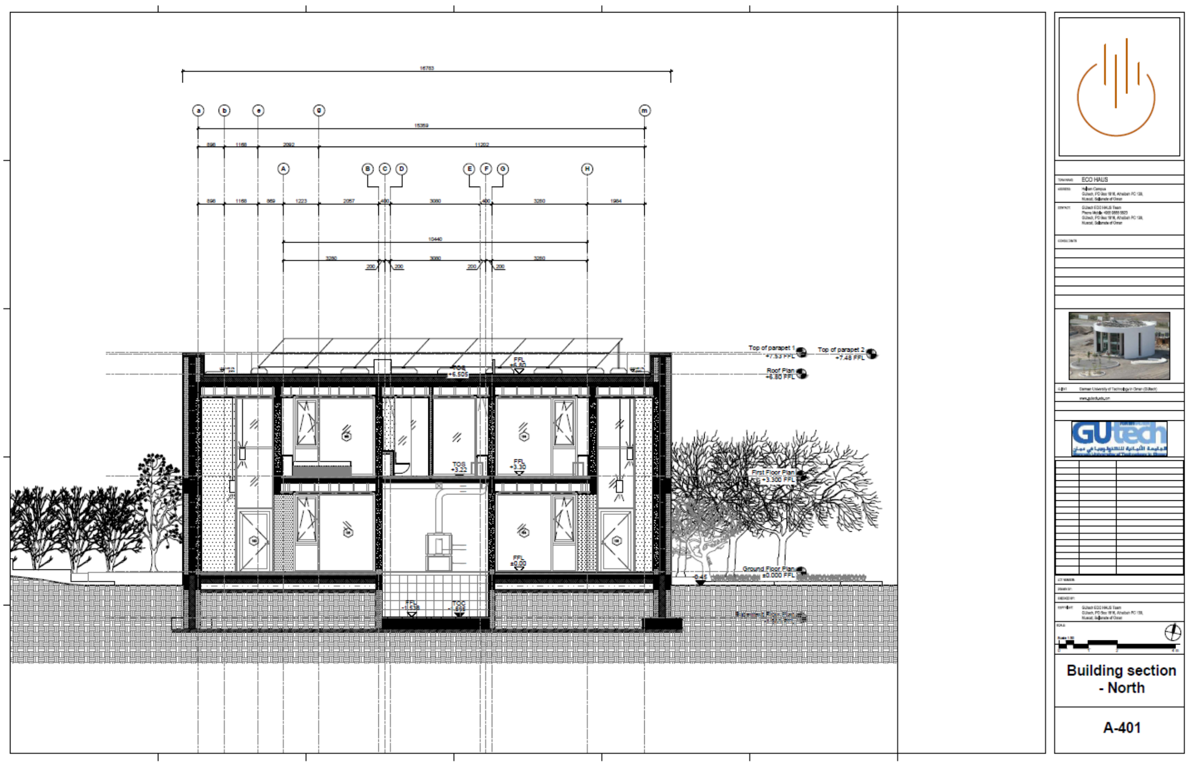
Appendix C: Reference LCB plans



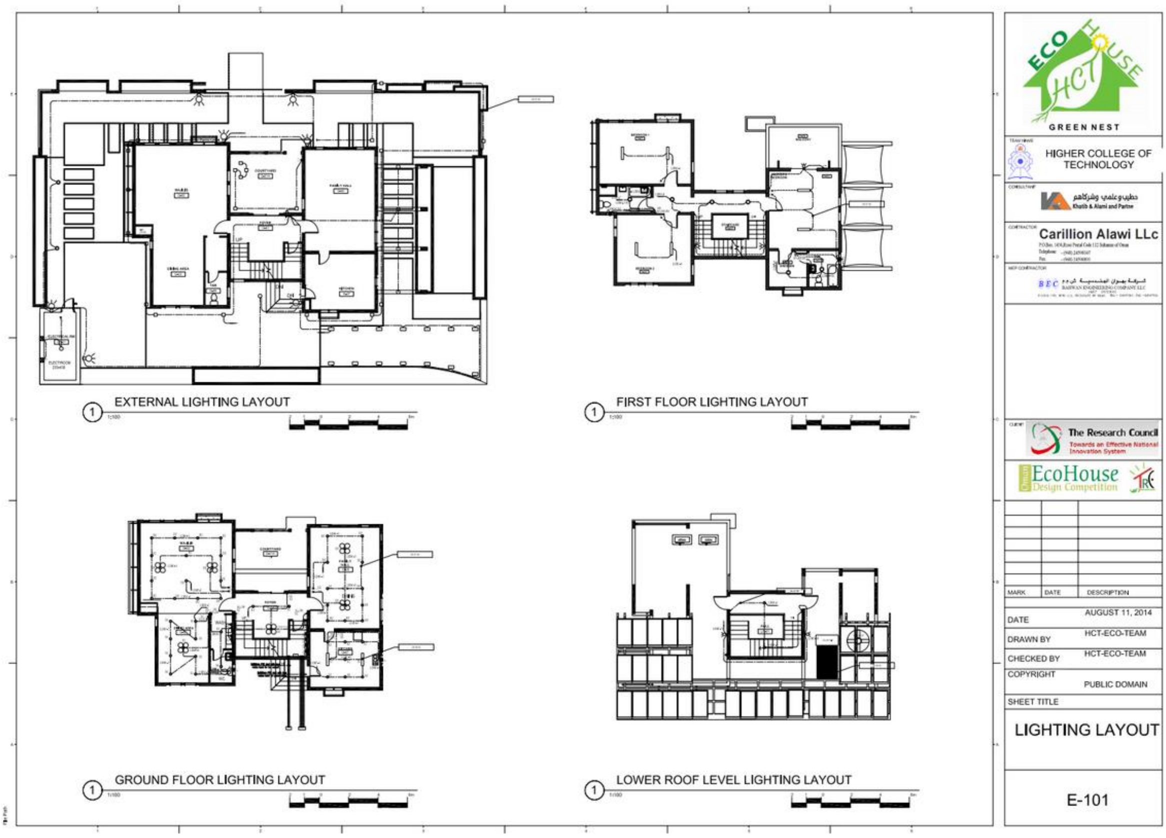


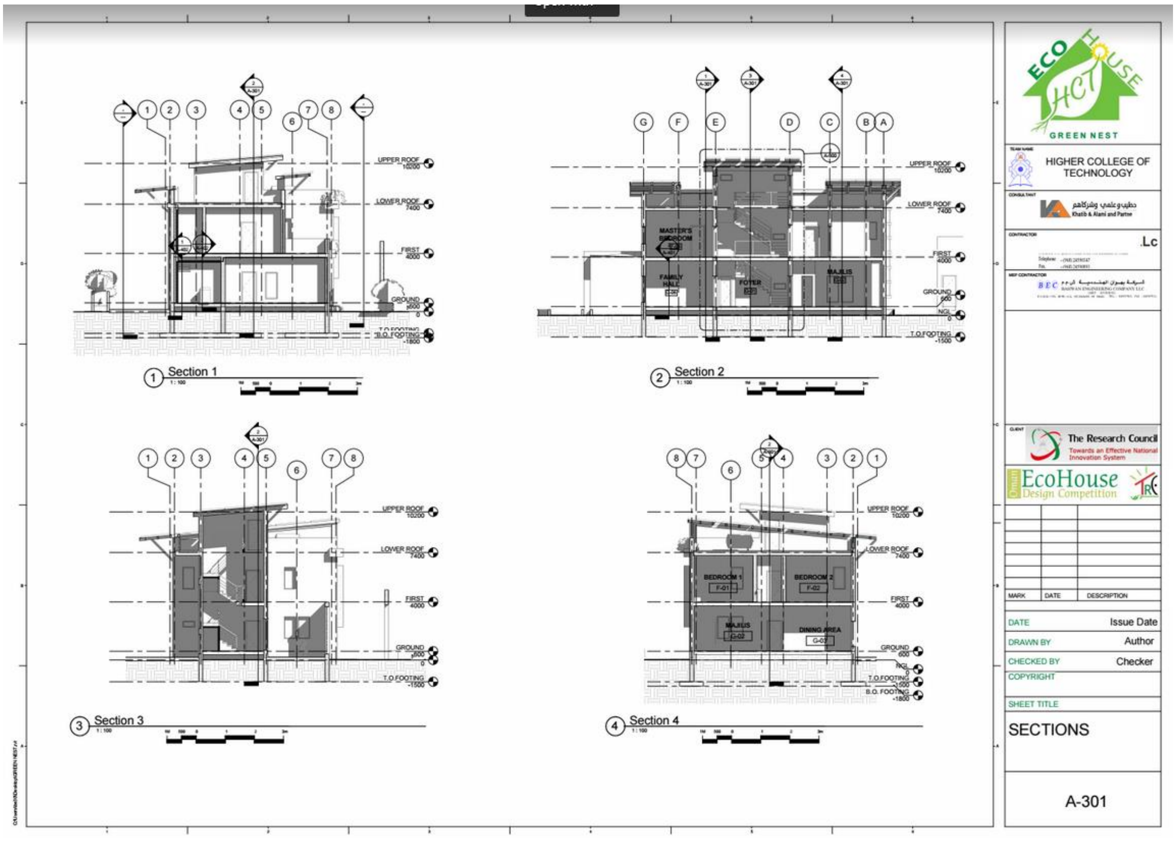
LCB1


ECO HAUS
GUtech
First floor plan
A-102

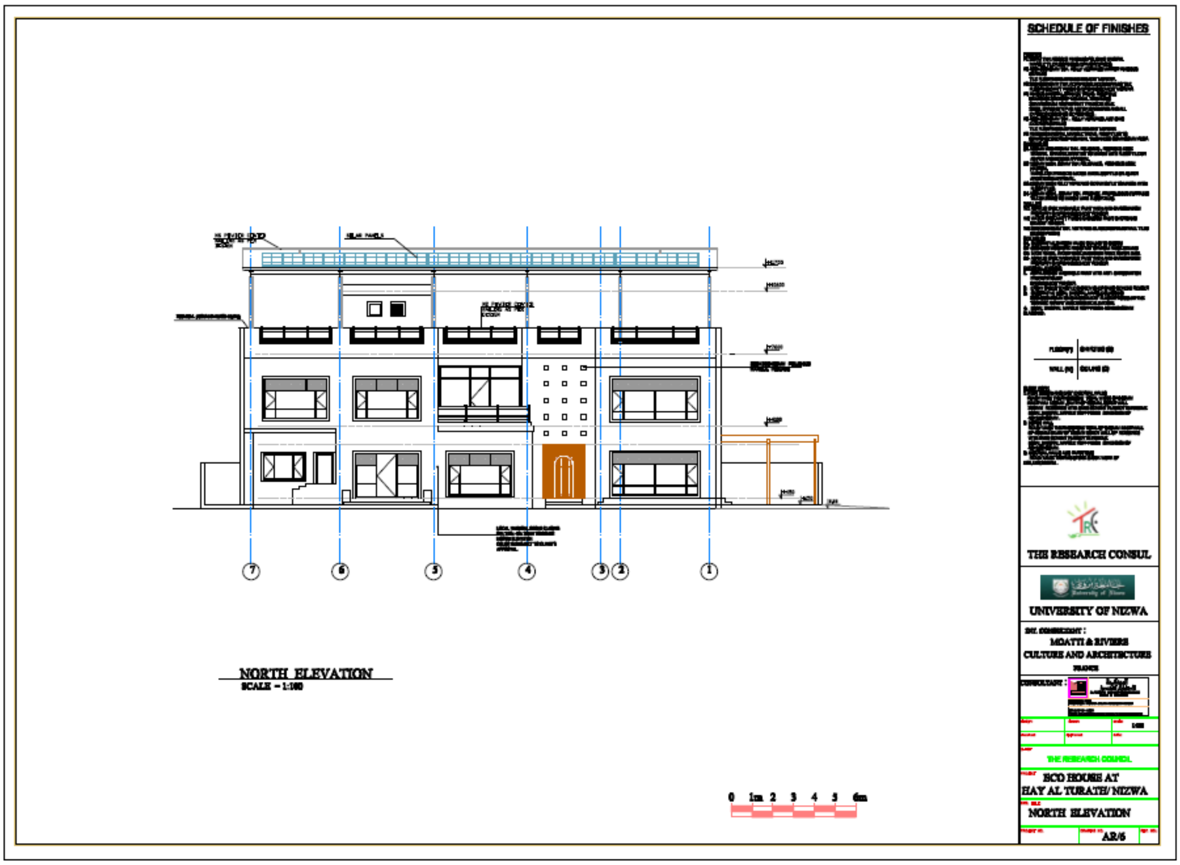

ECO HAUS
GUtech
Top of parapet 1
Top of parapet 2
Roof Plan
First Floor Plan
Ground Floor Plan
Building section - North
A-401

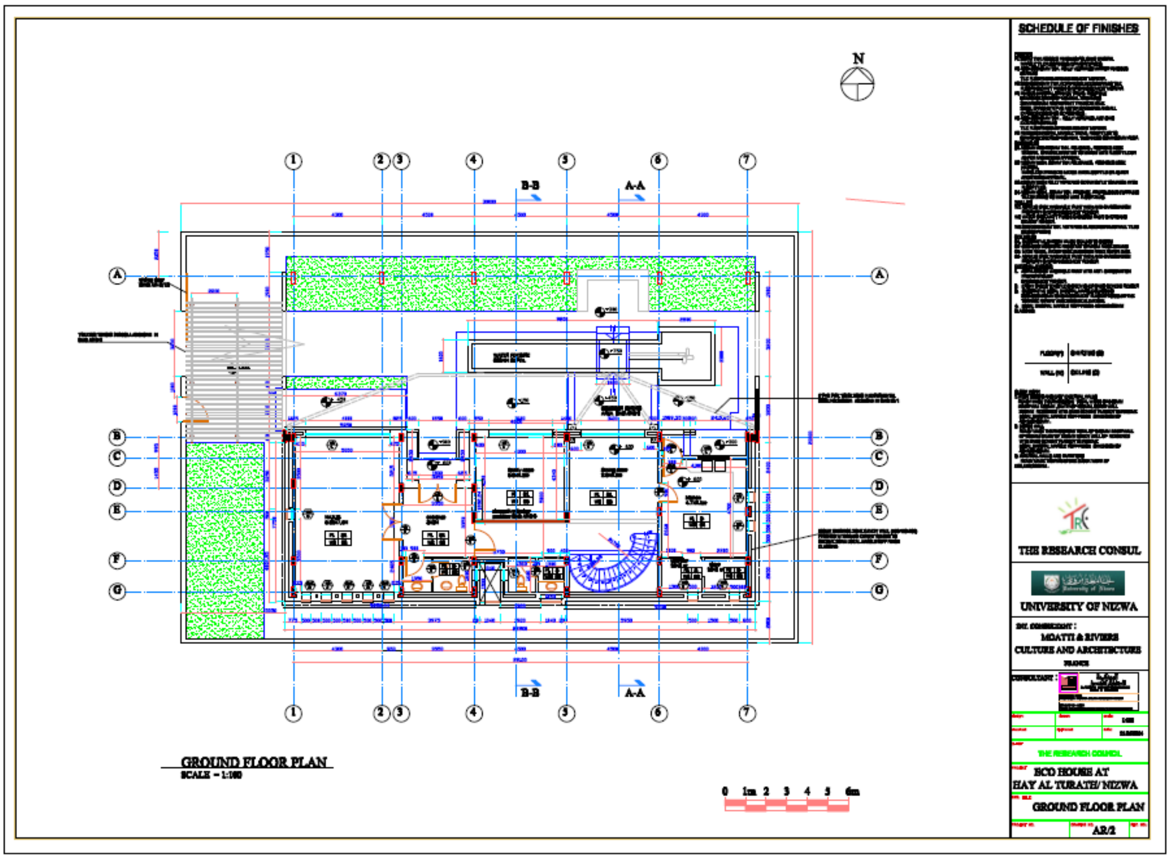
LCB2


EXTERNAL LIGHTING LAYOUT
FIRST FLOOR LIGHTING LAYOUT
GROUND FLOOR LIGHTING LAYOUT
LOWER ROOF LEVEL LIGHTING LAYOUT
GREEN NEST
HIGHER COLLEGE OF TECHNOLOGY
Carillion Alawi LLc
The Research Council
EcoHouse Design Competition
MARK
DATE
DESCRIPTION
DATE
AUGUST 11, 2014
DRAWN BY
HCT-ECO-TEAM
CHECKED BY
HCT-ECO-TEAM
COPYRIGHT
PUBLIC DOMAIN
SHEET TITLE
LIGHTING LAYOUT
E-101

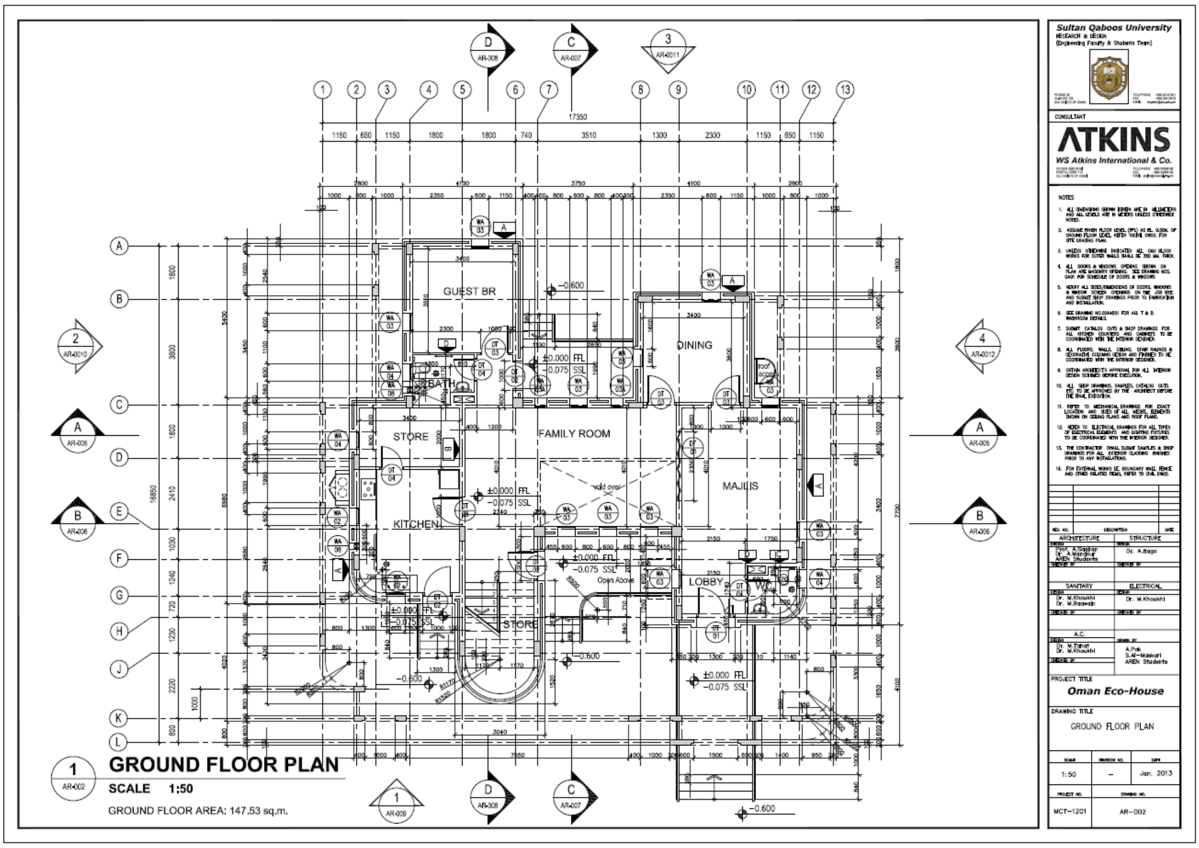

Section 1
Section 2
Section 3
Section 4
UPPER ROOF
LOWER ROOF
FIRST
GROUND
T.O.FOOTING
B.O.FOOTING
MASTER'S BEDROOM
FAMILY HALL
FOYER
MAJLIS
BEDROOM 1
BEDROOM 2
DINING AREA
GREEN NEST
HIGHER COLLEGE OF TECHNOLOGY
The Research Council
EcoHouse Design Competition
MARK
DATE
DESCRIPTION
DATE
Issue Date
DRAWN BY
Author
CHECKED BY
Checker
COPYRIGHT
SHEET TITLE
SECTIONS
A-301

LCB3

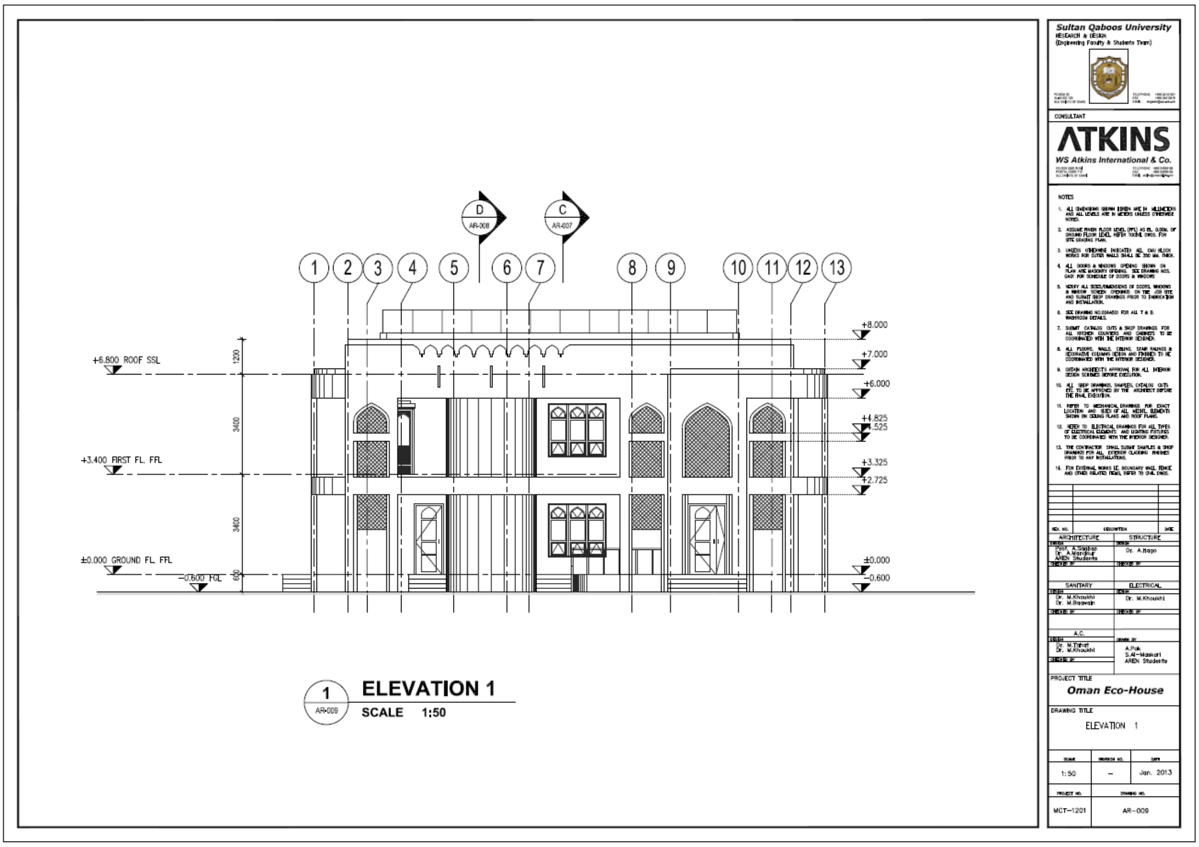

NORTH ELEVATION
SCALE - 1:100
SCHEDULE OF FINISHES
THE RESEARCH CONSUL
UNIVERSITY OF NIZWA
MOATTI & RIVIERE
CULTURE AND ARCHITECTURE
ECO HOUSE AT
HAY AL TURATH/ NIZWA
NORTH ELEVATION
AR/6


GROUND FLOOR PLAN
SCALE - 1:100
SCHEDULE OF FINISHES
THE RESEARCH CONSUL
UNIVERSITY OF NIZWA
MOATTI & RIVIERE
CULTURE AND ARCHITECTURE
ECO HOUSE AT
HAY AL TURATH/ NIZWA
GROUND FLOOR PLAN
AR/2

LCB4



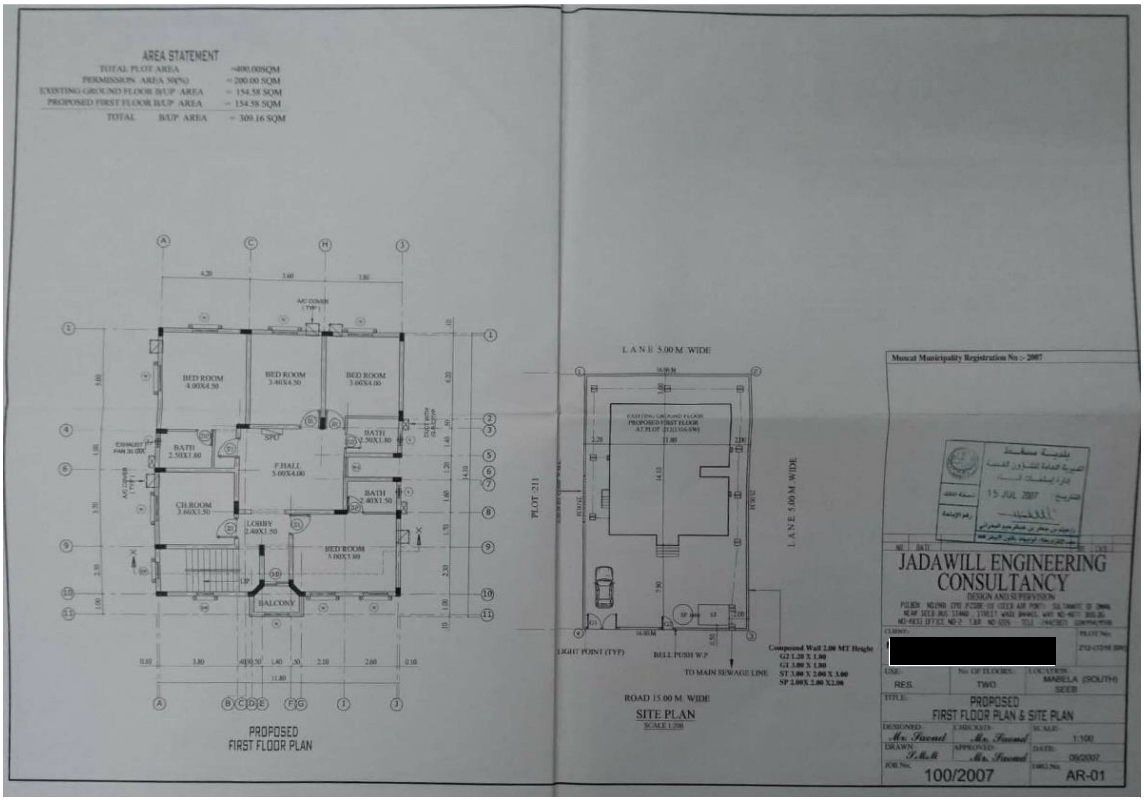
GROUND FLOOR PLAN
SCALE 1:50
GROUND FLOOR AREA: 147.53 sq.m.
GUEST BR
DINING
STORE
FAMILY ROOM
MAJLIS
KITCHEN
LOBBY
STORE
Sultan Qaboos University
ATKINS
WS Atkins International & Co.
Oman Eco-House
GROUND FLOOR PLAN
1:50
Jan. 2013
MCT-1201
AR-002

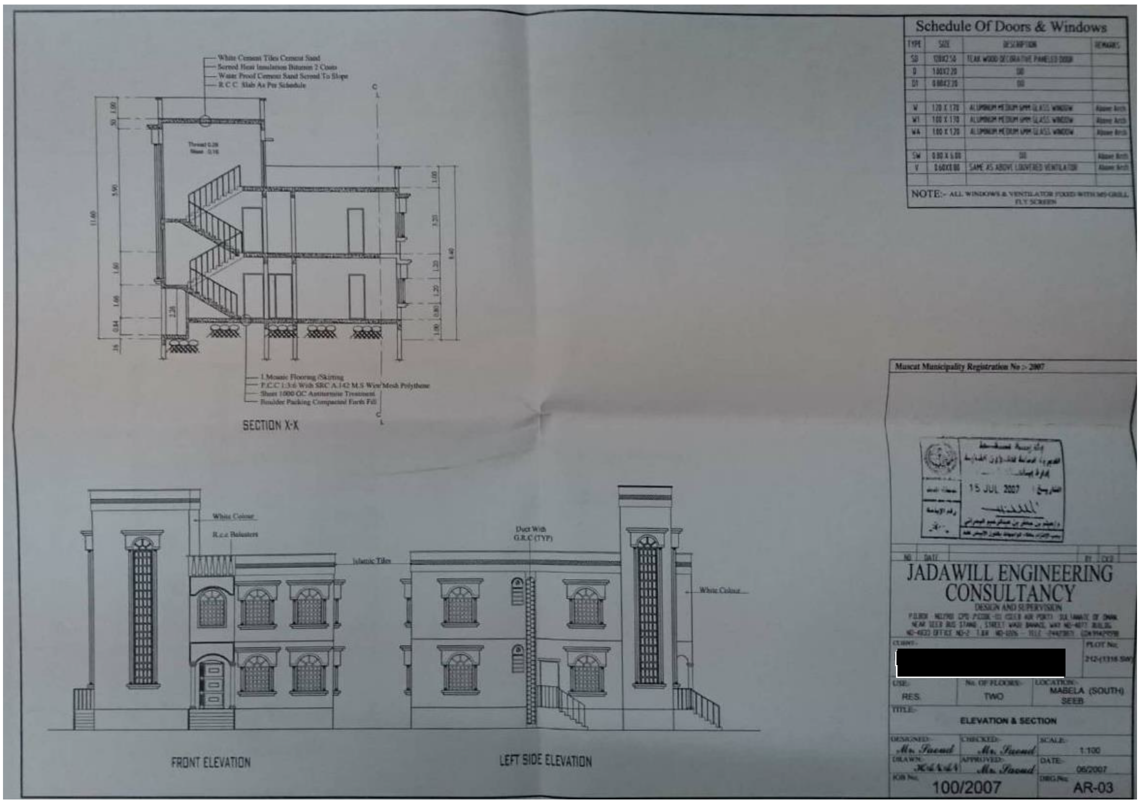


ELEVATION 1
SCALE 1:50
+6.800 ROOF SSL
+3.400 FIRST FL. FFL
±0.000 GROUND FL. FFL
-0.600 FGL
Sultan Qaboos University
ATKINS
WS Atkins International & Co.
Oman Eco-House
ELEVATION 1
1:50
Jan. 2013
MCT-1201
AR-009

LCB5

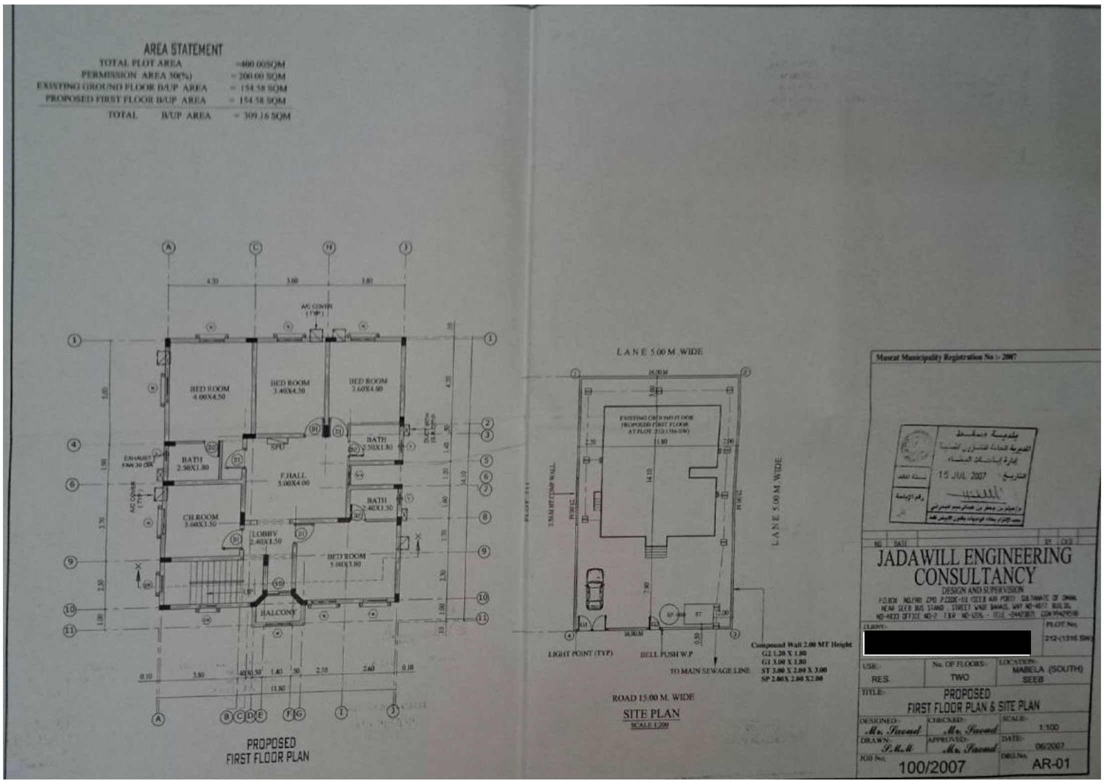
Appendix D: Reference CBs plans



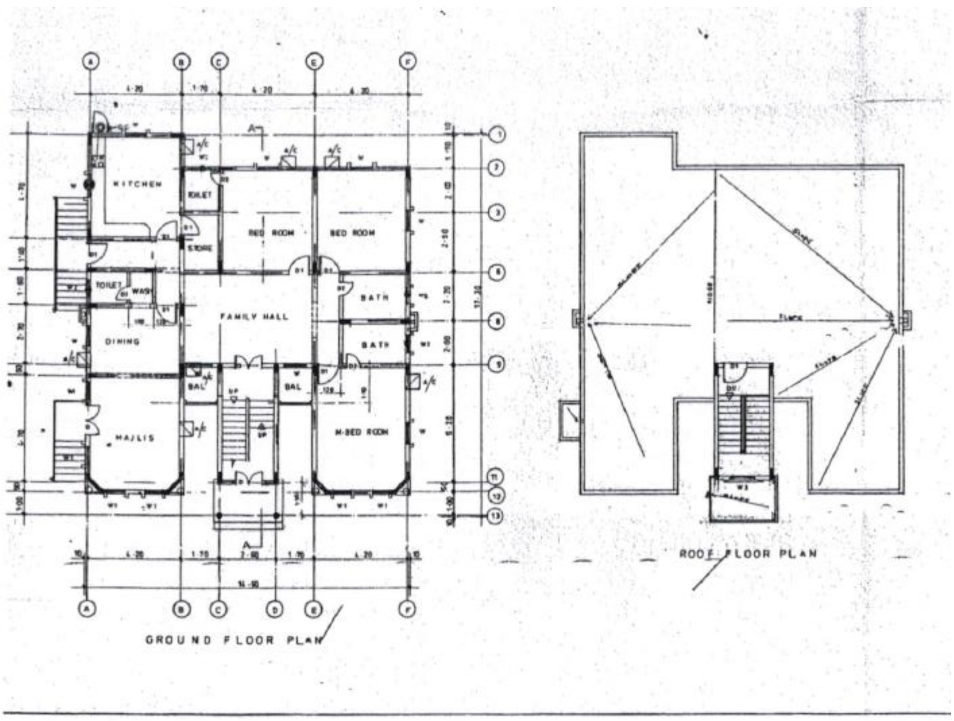


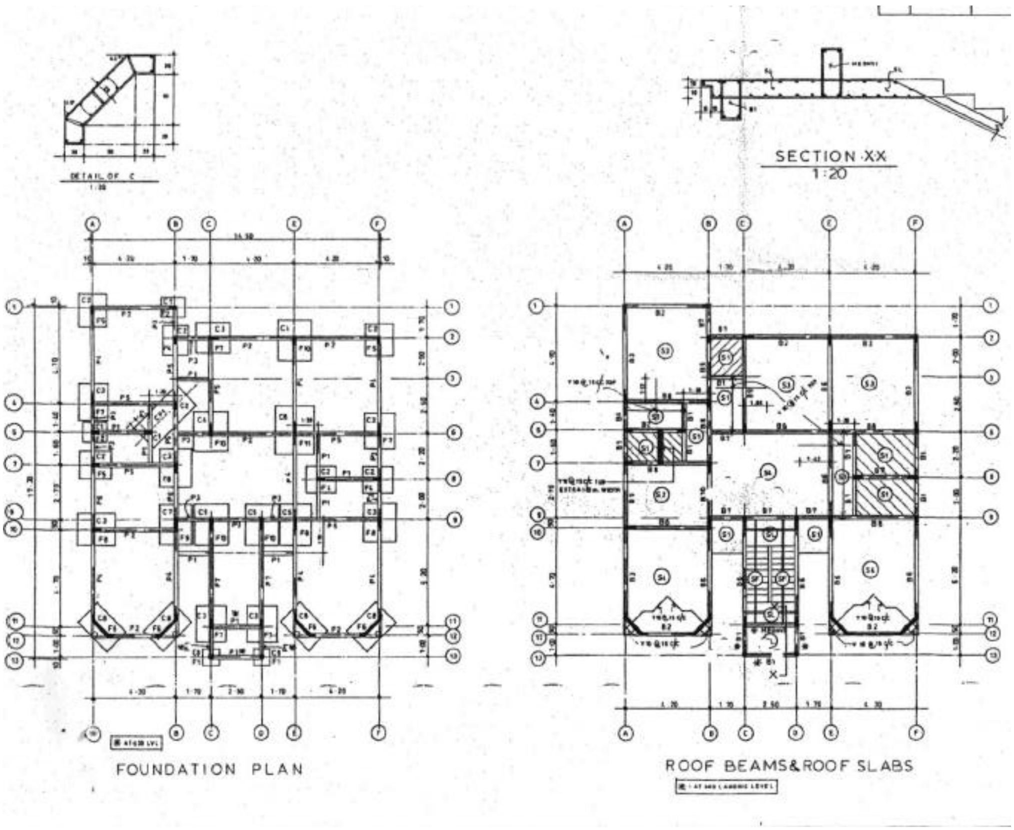
CB1


TOP OF PARAPET LVL.
TERRACE FLOOR LVL.
FIRST FLOOR LVL.
GROUND FLOOR LVL.
EST. GRADE LVL.
RIGHT SIDE ELEVATION
WHITE COLOUR SMOOTH FINISH PAINT (TYP)
G R C DECOR
GROOVES IN PLASTERING
STONE FINISH
DECORATION COLUMN DESIGN IN PLASTERING
WHITE COLOUR ALUM FRAME WITH LIGHT BLUE REFL GLASS (TYP.)
DOUBLE LEAF WOODEN DECOR PANEL DOOR
FRONT ELEVATION
SULTANATE OF OMAR

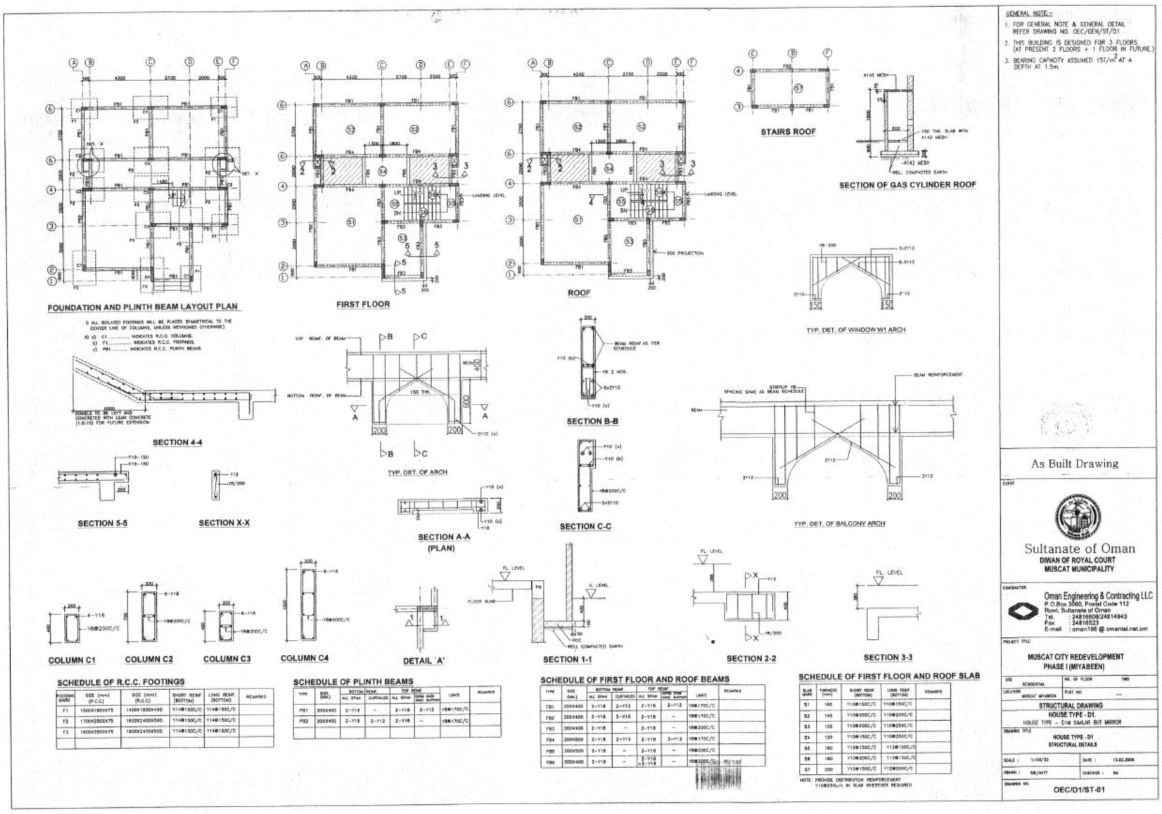

AREA STATEMENT
TOTAL PLOT AREA =400.00SQM
PERMISSION AREA 50(%) =200.00 SQM
EXISTING GROUND FLOOR B/UP AREA =154.58 SQM
PROPOSED FIRST FLOOR B/UP AREA =154.58 SQM
TOTAL B/UP AREA =309.16 SQM
PROPOSED FIRST FLOOR PLAN
LANE 5.00 M. WIDE
ROAD 15.00 M. WIDE
SITE PLAN
15 JUL 2007
JADAWILL ENGINEERING CONSULTANCY
DESIGN AND SUPERVISION
[redacted]
RES.
TWO
MABELA (SOUTH) SEEB
PROPOSED FIRST FLOOR PLAN & SITE PLAN
1:100
06/2007
100/2007
AR-01

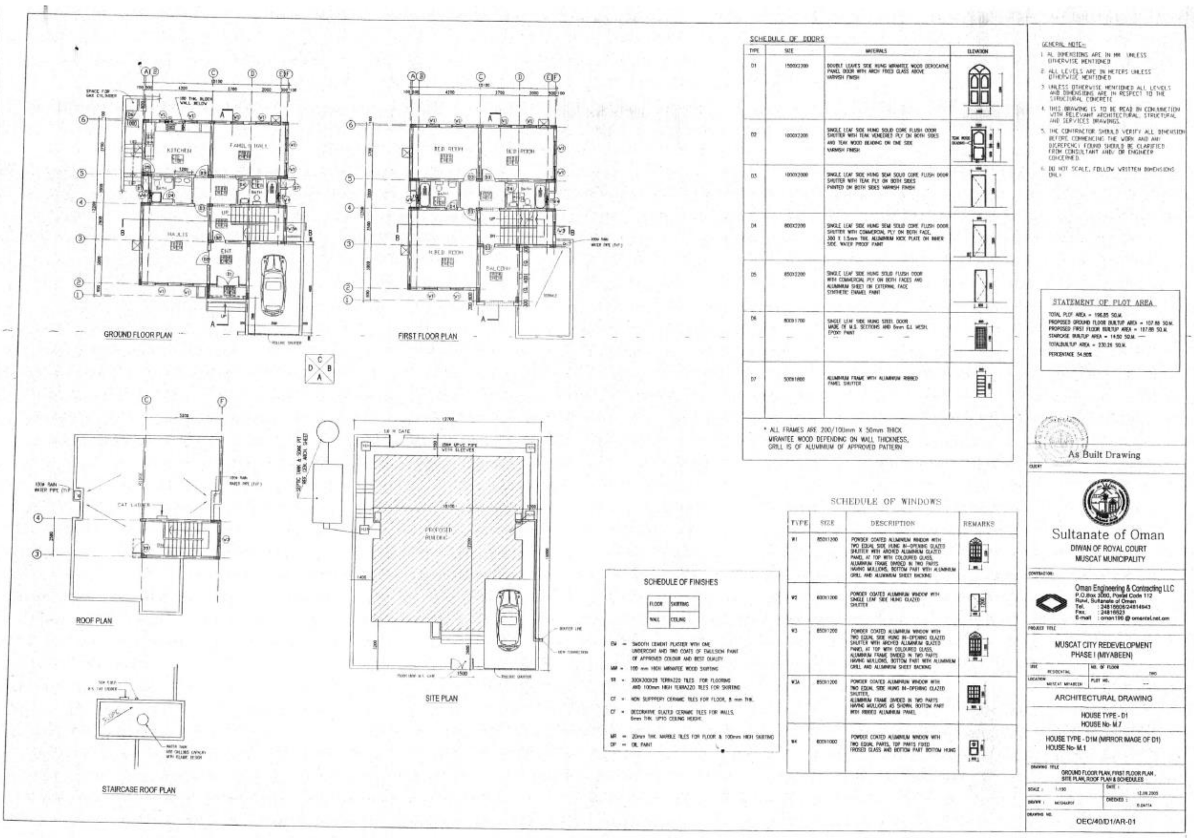
CB2


KITCHEN
TOILET
STORE
BED ROOM
BED ROOM
FAMILY HALL
BATH
BATH
DINING
MAJLIS
M-BED ROOM
BAL
BAL
GROUND FLOOR PLAN
ROOF FLOOR PLAN

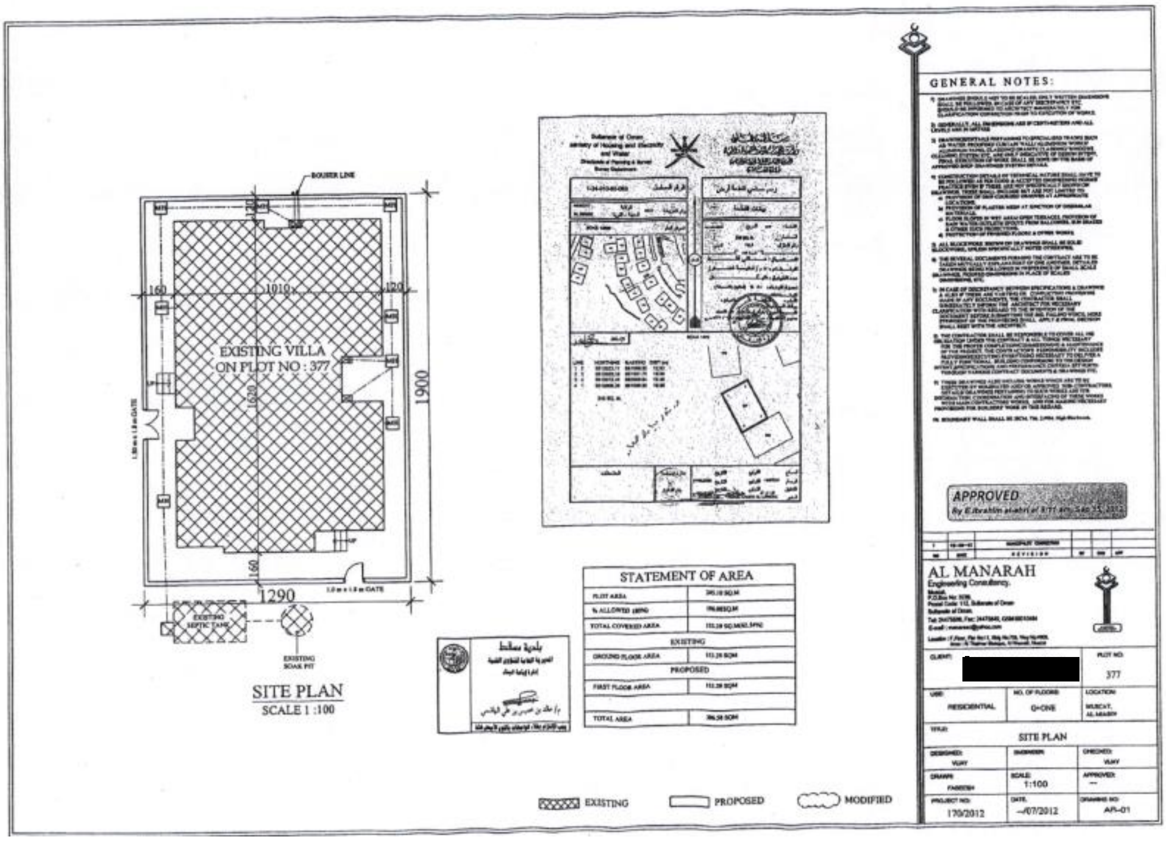

DETAIL OF C
SECTION XX
1:20
FOUNDATION PLAN
ROOF BEAMS&ROOF SLABS

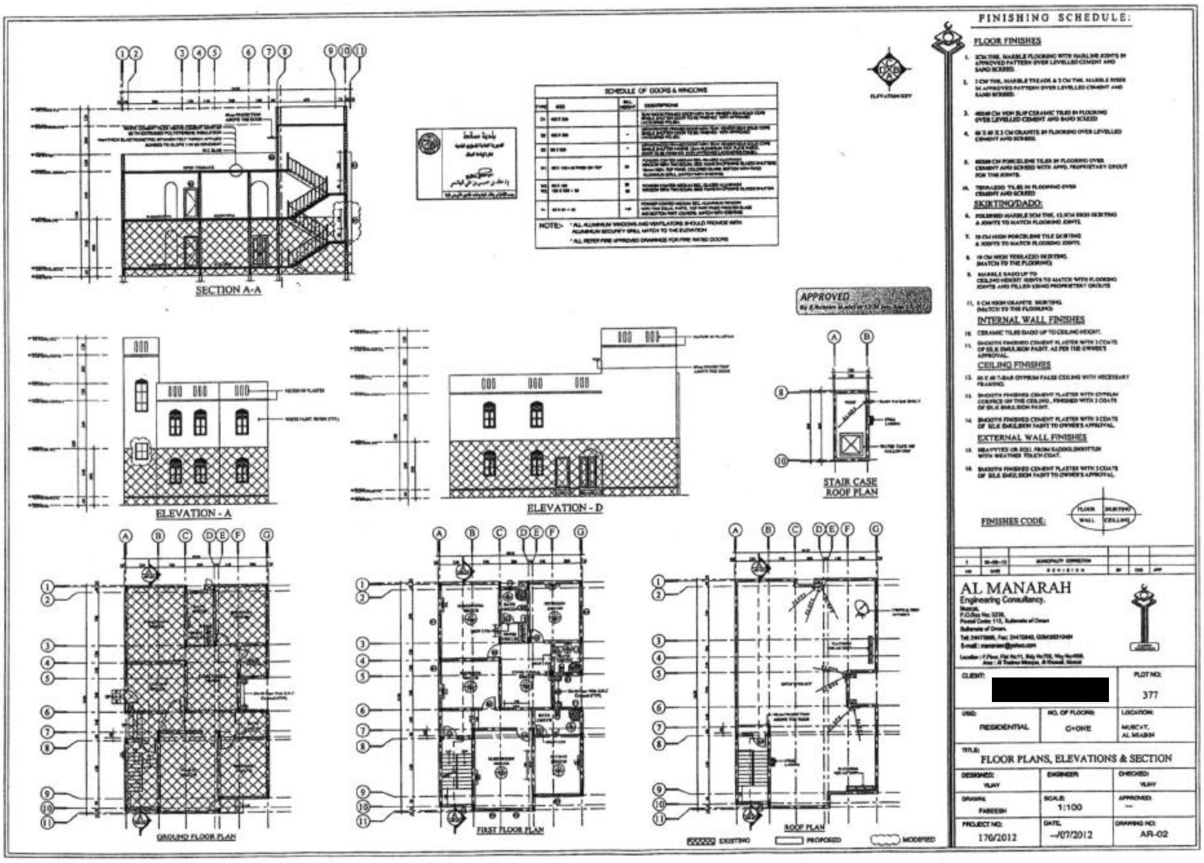
CB3


FOUNDATION AND PLINTH BEAM LAYOUT PLAN
FIRST FLOOR
ROOF
STAIRS ROOF
SECTION OF GAS CYLINDER ROOF
TYP. DET. OF WINDOW W1 ARCH
SECTION 4-4
SECTION B-B
TYP. DET. OF ARCH
SECTION 5-5
SECTION X-X
SECTION A-A (PLAN)
SECTION C-C
TYP. DET. OF BALCONY ARCH
COLUMN C1
COLUMN C2
COLUMN C3
COLUMN C4
DETAIL 'A'
SECTION 1-1
SECTION 2-2
SECTION 3-3
SCHEDULE OF R.C.C. FOOTINGS
SCHEDULE OF PLINTH BEAMS
SCHEDULE OF FIRST FLOOR AND ROOF BEAMS
SCHEDULE OF FIRST FLOOR AND ROOF SLAB
GENERAL NOTE:-
As Built Drawing
Sultanate of Oman
DIWAN OF ROYAL COURT
MUSCAT MUNICIPALITY
Oman Engineering & Contracting LLC
MUSCAT CITY REDEVELOPMENT
PHASE I (MIYABEEN)
STRUCTURAL DRAWING
HOUSE TYPE - D1
OEC/D1/ST-01


SCHEDULE OF DOORS
GENERAL NOTE:-
GROUND FLOOR PLAN
FIRST FLOOR PLAN
STATEMENT OF PLOT AREA
As Built Drawing
ROOF PLAN
SITE PLAN
SCHEDULE OF WINDOWS
SCHEDULE OF FINISHES
Sultanate of Oman
DIWAN OF ROYAL COURT
MUSCAT MUNICIPALITY
Oman Engineering & Contracting LLC
MUSCAT CITY REDEVELOPMENT
PHASE I (MIYABEEN)
ARCHITECTURAL DRAWING
STAIRCASE ROOF PLAN
OEC/40/D1/AR-01

CB4


GENERAL NOTES:
EXISTING VILLA
ON PLOT NO : 377
1290
1900
SITE PLAN
SCALE 1 :100
STATEMENT OF AREA
EXISTING
PROPOSED
TOTAL AREA
APPROVED
AL MANARAH
Engineering Consultancy.
CLIENT:
[redacted]
PLOT NO:
377
RESIDENTIAL
G+ONE
SITE PLAN
1:100
170/2012
--/07/2012
AR-01
EXISTING
PROPOSED
MODIFIED


FINISHING SCHEDULE:
FLOOR FINISHES
SKIRTING/DADO:
INTERNAL WALL FINISHES
CEILING FINISHES
EXTERNAL WALL FINISHES
FINISHES CODE:
SCHEDULE OF DOORS & WINDOWS
SECTION A-A
APPROVED
ELEVATION - A
ELEVATION - D
STAIR CASE ROOF PLAN
GROUND FLOOR PLAN
FIRST FLOOR PLAN
ROOF PLAN
AL MANARAH
Engineering Consultancy.
CLIENT:
[redacted]
PLOT NO:
377
RESIDENTIAL
G+ONE
FLOOR PLANS, ELEVATIONS & SECTION
1:100
170/2012
--/07/2012
AR-02
EXISTING
PROPOSED
MODIFIED

LCB5

Appendix E: LCB monitory system

-NOTE-	*Additional specifications are listed in the CR1000 Specifications Sheet.*
Temperature Range	• -25° to +50°C (standard) • -55° to +85°C (extended)
Maximum Scan Rate	100 Hz
Analog Inputs	16 single-ended or 8 differential (individually configured)
Pulse Counters	2
Switched Excitation Channels	3 voltage
Communications/Data Storage Ports	• 1 CS I/O • 1 RS-232 • 1 parallel peripheral
Switched 12 Volt	1
Digital Ports	• 8 I/Os or 4 RS-232 COM I/O ports can be paired as transmit and receive for measuring smart serial sensors. • Certain digital ports can be used to count switch closures.
Input Voltage Range	±5 Vdc
Analog Voltage Accuracy	±(0.06% of reading + offset) at 0° to 40°C
Analog Resolution	0.33 µV
A/D Bits	13
Power Requirements	9.6 to 16 Vdc
Real-Time Clock Accuracy	±3 min. per year (Correction via GPS optional.)

Protocols Supported	PakBus, Modbus, DNP3, FTP, HTTP, XML, POP3, SMTP, Telnet, NTCIP, NTP, SDI-12, SDM
CE Compliance Standards to which Conformity Is Declared	IEC61326:2002
Warranty	3 years
Dimensions	• 23.8 x 10.1 x 5.4 cm (9.4 x 4.0 x 2.1 in.) • 25.2 x 10.2 x 7.1 cm (9.9 x 4.0 x 2.8 in.) with CFM100 or NL116 attached
Weight	1.0 kg (2.1 lb)

Modbus Communication

- Protocol: Modbus RTU (binary)
- Baud Rates: 2,400, 4,800, 9,600,19,200, and 38,400 baud
- Duplex: Half (two-wire plus common)
- Parity (default): N81 (no parity, eight data bits, one stop bit)
- Modbus Buffer: 256 bytes
- Response Time (typical): 5 to 25 milliseconds

EIA RS-485 Interface

- Driver Output Voltage (Open Circuit): ± V maximum
- Driver Output Voltage (54Ω load): ± 1.5 V minimum
- Driver Output Current (54Ω load): ± 60 mA typical
- Driver Output Rise Time (54Ω || 50 pF load): 900 nS typical
- Receiver Common-Mode Voltage Range: –7 to +12 Vdc maximum
- Receiver Sensitivity: ±200 mV

- Receiver Bus Load: 1/8 unit load

Electrical

- Line powered
- Operating Voltage Range: –20% to +15% of nominal
- Power Line Frequency: 50 or 60 Hz
- CT Input: 0.333 Vac nominal, 0 to 0.5 Vac operating, 3 Vac maximum

Measurement Configurations

Models available for:

- Single phase: two or three wire
- Three phase: four wire wye
- Three phase: three wire delta
- Three phase: four wire delta

Accuracy

WattNode Modbus

0.5% nominal (see manual for details)

WattNode Revenue Modbus

- 0.5% nominal (see manual for details)
- Meets the accuracy requirements of the ANSI C12.1 standard when used with CCS CTs rated for IEEE C57.13 class 0.6 accuracy (see Revenue Grade CTs).
- Models RWNC-3Y-208-MB, RWNC-3D-240-MB and RWNC-3Y-480-MB are certified by MET Laboratories to meet ANSI C12.1. MET Labs is a nationally recognized testing laboratory (NRTL).

Regulatory

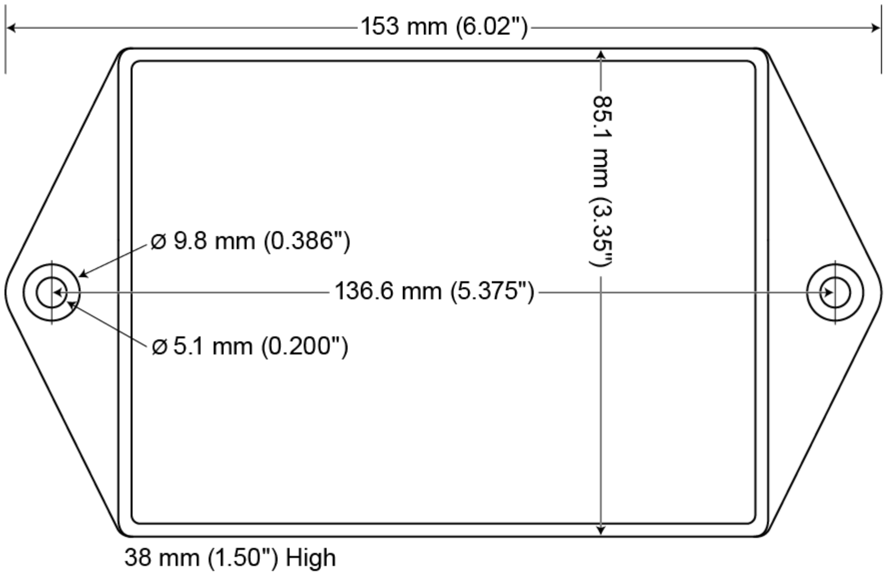
- FCC Class B, EN 55022 Class B
- UL and cUL Listed (UL 61010-1), file number E312220
- CE Mark and RoHS Declaration of Conformity
- Immunity: EN 61326: 2002 (Industrial Locations)

Environmental

- Operating Temperature: –30°C to +55°C (–22°F to +131°F)
- Altitude: Up to 2000 m (6560 ft)
- Operating Humidity: 5 to 90% relative humidity (RH) up to 40°C, decreasing linearly to 50% RH at 55°C.
- Pollution: POLLUTION DEGREE 2 – Normally only non-conductive pollution; occasionally, a temporary conductivity caused by condensation must be expected.
- Indoor Use: Suitable for indoor use.

- Outdoor Use: Suitable for outdoor use when mounted inside an electrical enclosure (Hammond Mfg., Type EJ Series) that is rated NEMA 3R or 4.

Mechanical



Case Dimensions

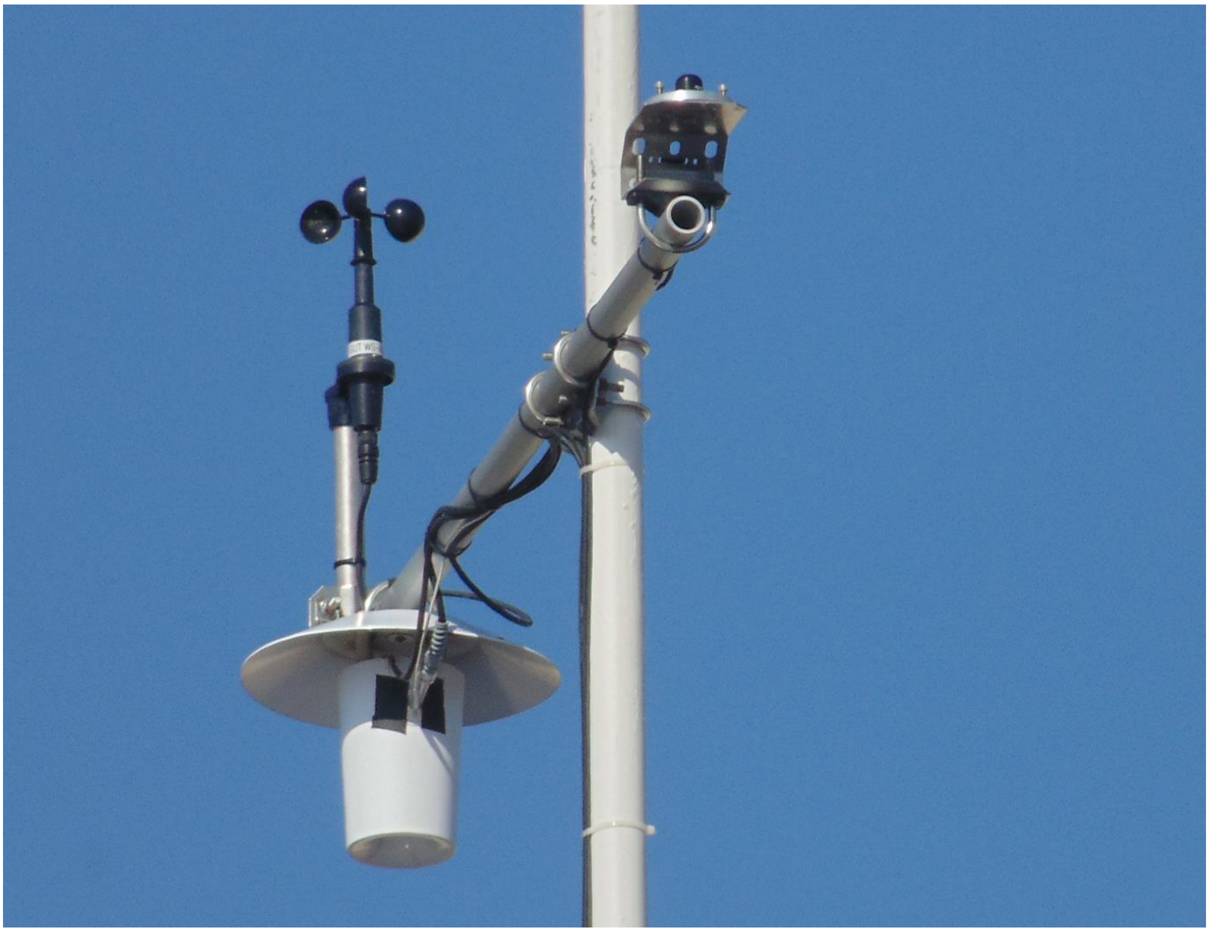
(Click on the image for a larger view.)

- Enclosure:
    - High impact, ABS plastic
    - Flame Resistance Rating: 94V-0, IEC FV-0
    - Size: 5.63 × 3.34 × 1.5 in. (143 × 85 × 38 mm)
    - Weight: 10.8 oz (305 g)
- Connectors: Euroblock style pluggable screw terminal blocks
    - Green: 22 to 12 AWG (0.32 to 2.5 mm^2), 600 V
    - Black: 22 to 12 AWG (0.32 to 2.5 mm^2), 300 V

Modbus is a registered trademark of Modbus Organization, Inc.

Current transformer photo

	OPTOEMU-ACT-0750-050	OPTOEMU-ACT-0750-100	OPTOEMU-ACT-0750-250
Rated Current (primary)	50 amps	100 amps	250 amps
Output (secondary)	0.333 VAC	0.333 VAC	0.333 VAC
Dimensions	2.38 x 2.40 x 0.90 in. (6.04 x 6.10 x 2.29 cm)	2.38 x 2.40 x 0.90 in. (6.04 x 6.10 x 2.29 cm)	2.38 x 2.40 x 0.90 in. (6.04 x 6.10 x 2.29 cm)
Inner Diameter	0.78 in. (2.0 cm)	0.78 in. (2.0 cm)	0.78 in. (2.0 cm)
Leads	8 ft (2.4 m), 22 AWG, twisted pair	8 ft (2.4 m), 22 AWG, twisted pair	8 ft (2.4 m), 22 AWG, twisted pair
Accuracy	± 0.75% from 1% to 120% of rated primary current	± 0.75% from 1% to 120% of rated primary current	± 0.75% from 1% to 120% of rated primary current
Phase Angle	± 0.5 degrees (30 min) from 1% to 120% of rated current	± 0.5 degrees (30 min) from 1% to 120% of rated current	± 0.5 degrees (30 min) from 1% to 120% of rated current
Agency Approvals	UL, CE, RoHS	UL, CE, RoHS	UL, CE, RoHS
Warranty*	5 years*	5 years*	5 years*
* Original manufacturer’s warranty applies. See http://www.ccontrolsys.com/w/Warranty			



Weather station

- Air Temperature Sensor:
  - Range: -13° to +122°F (-25° to +50°C)
  - Accuracy: +/- 2.7°F (+/- 1.5°C)
- Relative Humidity Sensor:
  - Range: 0 to 100%
  - Accuracy: +/- 6% @ 90% to 100% RH, +/- 3% @ 0% to 90% RH
- Solar Radiation Sensor:
  - Accuracy: ± 3%
- Wind Speed Sensor:
  - Starting threshold: 0.9 mph (0.4 m s-1)

- Input required: 9.6 to 16 VDC±10% (100-240 VAC/16 VDC transformer provided with powered stations) or solar panels
- Power backup: “Gel-cell” 12 VDC battery (provided with station)

Specifications

Sensing Element	Sensirion SHT75
Communication Standard	SDI-12 V1.3 (responds to a subset of commands)
Housing Material	Anodized aluminum
Housing Classification	IP65 (NEMA 4)
Sensor Protection	Outer glass-filled polypropylene cap. Inner expanded PTFE filter. Filter material has a porosity of 64% and a pore size of < 3µm.
Supply Voltage	• The supply voltage is typically powered by the datalogger's 12 V supply. • 7 to 28 Vdc (for serial numbers E13405 and newer) • 6 to 18 Vdc (for older models)
Typical Current Drain	• 120 µA (quiescent)

	• 1.7 mA (measurement takes 0.7 s)
EMC Compliance	Tested and conforms to IEC61326:2002.
Operating Temperature Range	-40° to +70°C
Diameter	• 1.2 cm (0.5 in.) at sensor tip • 1.8 cm (0.7 in.) at cable end
Length	18.0 cm (7.1 in.) including strain relief
Weight	150 g (5.3 oz) with 3.05-m (10-ft) cable

Relative Humidity

Measurement Range	0 to 100% RH (-20° to +60°C)
Output Resolution	0.03% RH
Accuracy	• ±2% (10% to 90% range) at 25°C • ±4% (0% to 100% range) at 25°C
Short-Term Hysteresis	< 1% RH
Temperature Dependence	Better than ±2% (-20° to +60°C)
Typical Stability	±1.0% per year
Response Time with Filter	< 20 s (63% response time in still air)
Calibration Traceability	NIST and NPL standards

Air Temperature

Measurement Range	-40° to +70°C
Output Resolution	0.01°C
Accuracy	• ±0.3°C (at 25°C) • ±0.4°C (5° to 40°C) • ±0.9°C (-40° to +70°C)
Response Time with Filter	< 120 s

Appendix F: R-BEET reports

CB1


Previous
Back to Start
User manual
Print Report
Mnthly energy consumption
kWh
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Design
Baseline
Axis Title
85.2
C1
C2
C3
B1
B2
B3
A1
A2
A3
Building performance
CO2 Emissions
Tones of CO2
Months
Design CO2 Emissions
Baseline CO2 Emissions

CB2


Previous
Back to Start
User manual
Print Report
Design
Baseline
Electronics
Lighting
HVAC
Mnthly energy consumption
kWh
Jan
Feb
Mar
May
Jun
Jul
Aug
Oct
Nov
Dec
Axis Title
Design
Baseline
59.2
C1
C2
C3
B1
B2
B3
A1
A2
A3
Building performance
CO2 Emissions
Tones of CO2
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Months

CB3


Previous
Back to Start
User manual
Print Report
Design
Baseline
Electronics
Lighting
Hot water
HVAC
Mnthly energy consumption
kWh
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Axis Title
Design
Baseline
C1
C2
C3
B1
B2
B3
A1
A2
A3
83.5
0
Building performance
CO2 Emissions
Tones of CO2
Months
Design CO2 Emissions
Baseline CO2 Emissions

CB4